Quantification of Wildfire Risk in South-West Western Australia

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Regards,

Ashley Kirvan (June 2005)
Abstract
In the South-West forests of Western Australia, wildfires present a danger to people, property, infrastructure and biodiversity. Currently, wildfire management in the region focuses on broad-scale hazard reduction, in the form of prescribed burning. The management of assets in the region may be enhanced by a quantitative understanding of risk, as defined in the Australian Standard for Risk Management. This allows a broader understanding of the factors affecting the risk to an asset. This study applies a return period analysis to develop a quantitative estimate of wildfire risk.

Fire data was obtained from the Department of Conservation and Land Management. This data consisted of the occurrence and locations of wildfires over a seventeen year period, as well as the fuel load over the forest. Relevant weather information was obtained from the Bureau of Meteorology. These data were used to simulate fire events over a 100 year period. An extreme value distribution was developed and a return period distribution of fire intensities found for the forest. The forest area was separated into a 10km x 10km square grid. A return period distribution was determined for each square, by utilising the probability of a fire occurring and the fuel load in each. This resulted in fire risk maps for the South-West forest.

This study follows from previous work by Nicol (2004 unpublished), in which a return period distribution for wildfire intensity was determined for the entire forest. This study improves the estimation of the return period distribution, and includes spatial information concerning fuel load and ignition probability in the estimate of risk. As such, this study is a step forward in the field of quantitative wildfire risk estimation. Additionally, the application of fire spread modelling to capture spatial variation in risk has been investigated, by examining a simple elliptical fire model.

It was found that the variation in risk across the forest had a greater dependence on the probability of a fire igniting than the fuel load in the area. Also, prescribed burning is seen to be most effective under a frequent burning rotation of 3.5-8 years. It was concluded that there is potential for the application of quantitative risk assessment for asset management in fire-prone areas, within a risk-based management framework. In particular, a quantitative assessment has the potential to enhance decision-making by improving understanding of the causes of risk, considering a broader suite of mitigation options, and providing a basis for measuring the impacts of mitigation strategies.
Glossary

Bushfire: See Wildfire.

Cumulative distribution function (CDF): The integral of the probability distribution function, the cumulative distribution function gives the probability that a variable takes on a value less than or equal to any specified number.

Fire Danger Index (FDI): An aggregate measure of weather conditions, determined using the Forest Fire Behaviour Tables, which indicates the expected rate of a fire front under standard fuel conditions.

Fire regime: The intensity, frequency, seasonality and type of fire (Ellis et al. 2004).

Fire retardant: A substance or treatment, incorporated in or applied to a material, which suppresses or delays the combustion of that material (Standards Australia 1999).

Forest Fire Behaviour Tables: (FFBT) The empirically-based method used by the Department of CALM to estimate the rate of wildfire spread under known fuel and weather conditions.

Fuel load: The amount of organic material on the forest floor which is available for combustion.

Intensity: The heat output of a burning fireline. It is measured in Wm$^{-1}$, which corresponds to the energy output per second per unit length of the fireline. The intensity of a fire indicates its potential for damage.

Monte Carlo Simulation: The process of using random input variables with a deterministic calculation in order to simulate a process.

Prescribed burning: The policy of burning areas of the forest under controlled conditions in order to reduce the fuel load.

Probability distribution function (PDF): A plot of all possible values that a parameter may take on, with a corresponding probability that each value occurs.
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tr>
<td>Return Period (T):</td>
<td>The average interval between events which equal or exceed a specified magnitude. The inverse of the return period is the probability that the chosen magnitude is exceeded in any one year.</td>
</tr>
<tr>
<td>Return Period Analysis:</td>
<td>A statistical method used to determine the expected frequency that an event of given magnitude is exceeded.</td>
</tr>
<tr>
<td>Risk:</td>
<td>The chance of something happening which will impact on objectives. It is measured in terms of likelihood and consequences (Standards Australia &amp; Standards New Zealand 2004).</td>
</tr>
<tr>
<td>Surface Moisture Content:</td>
<td>The water content of fine fuels on the forest floor. It is measured as a percentage of oven-dry weight. This parameter affects the flammability of a fuel and the amount which is available to burn.</td>
</tr>
<tr>
<td>Wildfire</td>
<td>An uncontrolled fire burning in forest, scrub or grassland vegetation, also referred to as bushfire (Standards Australia 1999).</td>
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1 Introduction

1.1 Motivations

Wildfires, or bushfires, can be a danger to individuals, infrastructure, communities and the natural environment. Damage due to wildfire in the South-West forests of Western Australia has been conservatively estimated at $4.5 m annually (Ellis et al. 2004). Nationally, wildfire has the highest casualty rate of any category of natural disaster (Ellis et al. 2004).

The management authority (Department of Conservation and Land Management) has not yet applied the Australian / New Zealand Standard for Risk Management to its wildfire management operations, and concentrates its efforts on a policy of hazard reduction in the form of prescribed burning. Currently, any estimates of risk are considered from a qualitative standpoint only. As such, appropriate mitigation strategies for assets within areas of wildfire risk may be improved by a quantitative estimate of risk.

This study builds on the work by Nicol (2004 unpublished) which, while seminal to the methods employed in this study, was limited in some respects. Most importantly, the study included no spatial information, meaning that the estimate of risk applied to the entire forest but could not be focussed on a specific asset in question. Also, the study assumed a uniform distribution for an important input parameter, the surface moisture content, which does not accurately capture the variation of this parameter. These limitations are discussed and expanded upon in Section 3.2.

1.2 Aim

The aim of this study is to investigate and improve methods to estimate wildfire risk in the South-West forest of Western Australia. The study is carried out in the context and interest of engineering design, and the appropriate mitigation of wildfire impacts on assets of interest.

1.3 Specific Objectives

To achieve this aim, the following objectives are defined:

1. Review the current state of wildfire management, and of the state of wildfire science including fire behaviour and modelling.
2. Improve the application of return period techniques, as set out by Nicol (2004 unpublished). Return period analysis is commonly used in flood estimation and other applications to estimate the probability of an event occurring with some given magnitude. In the case of wildfires, magnitude is measured as intensity. To this end:

   a. Improve the estimation of intensity, by utilising distributions of weather variables rather than an assumed distribution of surface moisture content. This allows for a more complete and accurate application of the variables which govern the intensity of a fire.

   b. Develop an appropriate mechanism by which the intensity return period distribution for the forest may be scaled down to a region of interest. That is, spatial data is to be included in the estimate of risk such that spatial variation of risk may be seen, and the risk of damage to a specific asset may be determined.

3. Investigate methods for the application of spatial fire spread models for estimating risk. Specifically, examine the use of a simple model to simulate wildfire spread and intensity.

4. Suggest directions for future research.
2 Literature Review

This chapter consists of four parts. First, the extent, importance and impacts of fire in Western Australia are discussed in Section 2.1. Section 2.2 concerns the behaviour of fire and the factors which govern that behaviour. An understanding of these factors is important as their influence on the nature of a fire will influence risk. Section 2.3 is a discussion of the science of fire modelling, which is applied in this study in the estimate of risk. Section 2.4 discusses the current management regime, including the methods employed by the Department of CALM, and the relevant standards. Further, the necessities of risk management and for a quantitative understanding of risk are discussed.

2.1 Bushfire in Western Australia

2.1.1 Danger to life and property

"Bushfire events can have significant impacts on individuals, communities, and public and private assets: they can threaten human life and property, agricultural and forest production, animals, biodiversity, air and water quality, cultural heritage and infrastructure"

-Council of Australian Governments, National Inquiry into Bushfire Mitigation and Management, 2004

The quotation above highlights the diversity and extent of impacts from wildfire in Australia. Western Australia’s dry climate, plentiful bushland and large rural-urban interface make fire a potentially lethal natural disaster (Ellis et al. 2004). A report by the Bureau of Transport Economics (2001) puts the average annual cost of damage by wildfires in WA at $4.5 m. This figure includes only ‘disaster-level’ bushfires, where the total insurance cost was more than $10m. It does not include forestry losses, the hundreds of smaller fires which cause damage every year, and the substantial cost of mitigation activities. Nationwide, wildfire has taken 250 lives in the past 40 years, which is the greatest loss of life associated with any type of natural disaster (Ellis et al. 2004; Bureau of Transport Economics 2001).

More so than for other natural disasters, such as cyclones or severe storms, there is potential to mitigate against bushfires (Ellis et al. 2004). The Department of Conservation and Land Management undertakes substantial fuel reduction burning (prescribed burning) (Department of
CALM 2003a), and townships and property can be designed to withstand or avoid wildfire damage. Additionally, sufficient fire fighting resources are able to assist in suppressing a wildfire once it has begun. However, fire regime information in Australia is currently very limited, making it difficult to make fully informed mitigation and management decisions (Ellis et al. 2004). ‘Fire regime’ refers to the intensity, frequency, seasonality and type of fire (Ellis et al. 2004).

The problems of bushfire mitigation and management are likely to become more important to Australians. Cities and small estates are increasingly moving into bushland or semi-rural settings (Ellis et al. 2004). Additionally, the CSIRO submission to the Council of Australian Governments report states that climate change scenarios show that global warming is likely to increase the frequency, intensity and size of bushfires in Australia (Ellis et al. 2004).

2.1.2 Ecological consequence of wildfires

Australian flora and fauna are generally well-adapted to fire, with bushfires being a natural characteristic of Australian forests (Knox et al. 2001; Luke & McArthur 1978; Underwood & Christensen 1981). For example, Eucalypts survive fires by having thick insulative bark, or in the case of the shoot being damaged, resprouting from dormant buds on the trunk (Knox et al. 2001). Other plants are killed but have hard fire-resistant seeds, or propagules, which are stimulated by fire to flower after the event (Knox et al. 2001; Underwood & Christensen 1981). There is a well-defined series of plant succession following a wildfire, whereby opportunistic flora appear directly after an event and then disappear within a year or two. These are followed by common wildflowers, then finally the area becomes dominated by larger plants of a smaller number of species (Underwood & Christensen 1981).

Ecosystem structure is therefore a function of the fire regime, which can act to maintain or diminish biodiversity in Australian ecosystems (Keith et al. 2002). Intensity is probably the most significant factor in the effect of a single fire on flora (Chandler et al. 1983; Underwood & Christensen 1981), although the frequency of fire events in an area will also determine the ecosystem structure (Gill & Catling 2002; Keith et al. 2002).

High intensity or high frequency fires will have the most impact on biodiversity. In terms of the influence of a high frequency regime, a study by Tolhurst (1996) in Victoria concluded that while all native species did have regenerative strategies to deal with fire, repeated burning
Literature Review
depletes these reserves. Therefore frequent burning has the capacity to significantly alter the species and diversity of the forest, in particular the understorey which is most affected (Tolhurst 1996). This change in vegetation also alters the habitat structure for fauna, and so can reduce the abundance and species richness of mammals, birds and insects (Gill & Catling 2002; Keith et al. 2002). Also, the passage of a single fire will result in the local extinction of fauna (Gill & Bradstock 1995), which can be serious if a threatened species exists in a confined burnt area.

Alternatively, intense low-frequency fires may be a danger. If the intervals between fires are too long, the propagules in the system may not persist until the next fire (Gill & Catling 2002). These propagules germinate due to the passage of an appropriate fire. In a long between-fire intervals, germination will only be successful in species which have long-dormant seeds, in which case the species will germinate and continue even when the population dies (Gill & Catling 2002). Single high-intensity events, driven by relatively old fuels, also have the potential to eliminate species, as in the case of alpine conifers described by Kirkpatrick and Dickinson (1984). Understorey species have also been observed to decline under low-frequency fires due to competitive exclusion over time (Keith & Bradstock 1994 as cited in; Keith et al. 2002). This is an example of a natural fire regime promoting biodiversity, whereby the competitive exclusion would not be allowed due to the disturbance produced from a moderately frequent fire regime.

The danger to biodiversity by fire disturbance is partially alleviated by the spatial heterogeneity, or patchiness, of burns. A high diversity of vegetation types may be seen in an area, due largely to this patchiness of burnt area within a single fire event (Clark et al. 2002). As a result, a small area can show a range of fire histories (Clark et al. 2002). This can allow a greater diversity of vegetation types and habitats in a relatively small area, due to the variation in area which is burnt with each fire.

The fire regime which is applied to a landscape will determine the species and ecosystem types which are found there. A single high-intensity fire has the potential to damage a wide range of flora and fauna, although flora generally has a variety of adaptations to for the species to survive fire, and fauna are often seen repopulating an area after a fire event (Wilson 1996). A high-frequency fire regime has the capacity to simplify the ecosystem structure by burning at short enough intervals that species cannot regenerate. Very little data has been collected on the effects of repeated fires on fauna population (Wilson 1996), although these populations will suffer in
response to the simplified vegetative and habitat structure (Gill & Catling 2002; Keith et al. 2002).

2.2 Fire behaviour

Once a fire ignites, the ability for a fire to spread and the characteristics of that fire are dependent on fuel characteristics and weather variables (Fosberg et al. 1999). Of particular interest to this study is the relative importance that these variables have on the intensity of a fire. Of note is the fact that of these variables, only fuel load is able to be managed by a management authority.

Fire intensity is the primary quantity considered in this study, and is defined as the output of heat energy per length of fireline, measured in kW/m. It is an indicator of the potential for damage of a wildfire, and also the difficulty of suppression (Catchpole 2002).

2.2.1 Important variables and their interactions

Fuel load

Fuel refers to the presence of dead organic material on the forest floor. This material can be separated into the categories of litter, trash and scrub fuels (Beck 1995). Litter refers to dead leaves, bark and small branches that falls from the forest canopy (Luke & McArthur 1978). This is the primary source of fuel governing fire behaviour in jarrah forests (Beck 1995).

Trash consists of dead tree branches and scrub debris, which are common in karri fuel complexes (Beck 1995). Jarrah fuels less than 10 years of age do not have a significant trash component (Beck 1995). Scrub is the flammable undergrowth on the forest floor, and the amount of scrub is a function of foliage height and density (Beck 1995). For the purpose of this study, the influence of scrub fuels on fuel load will be assumed negligible, as no information was provided by CALM regarding scrub load as part of their historical fire data.

Due to the dominance of litter fuels on fuel loading, this is the only category of fuel considered in this study. This corresponds with the Forest Fire Behaviour Tables (FFBT) which consider this category to be the major contributor to fire spread (Catchpole 2002).

Measurements of fuel load are usually expressed as a weight per unit area (Luke & McArthur 1978). This unit can be either determined from measurements of fuel depths or calculated from
the time since the last fire event. The second technique applies the number of yearly leaf falls which have occurred since the last event, and the canopy cover, which indicates the volume of litter in each fall (Beck 1995). This technique is discussed later in this dissertation in Section 4.2 and is expressed in Equation 4.1.

The amount of fuel that is immediately available to burn in a fire is a function of the fuel load and the moisture profile of the fuel bed, since wet components of the fuel are unable to burn (Beck 1995). As a result of the Department of CALM’s fuel reduction policy, which has been in effect since 1954 (Underwood et al. 1985), litter fuels in northern jarrah forests are generally less than 20 mm in depth. Such shallow litter beds generally do not show a significant moisture gradient, and so the moisture content is said to be constant throughout the fuel (Beck 1995). As such, if the surface moisture content (SMC) is below the moisture content which will extinguish a fire, the entire fuel mass is considered available for burning (Beck 1995).

Fuel load has a direct effect on the intensity of a wildfire (Luke & McArthur 1978; Muller 1993). This is because in a greater fuel load, there is more material to burn for a given rate of spread (see Equation 4.9). The Forest Fire Behaviour Tables, which are applied in this study, suggest that the rate of spread is also a directly proportional function of fuel load (Beck 1995). As a result, the FFBT predicts that a halving of the fuel load will result in a four-fold reduction in intensity, which is directly related to both fuel load and rate of spread (Fernandes & Botelho 2003). This relationship between fuel load and rate of spread is not supported by more recent studies (Cheney et al. 1993; McAlpine 1995; Burrows 1999b). This may mean that the effect of fuel reduction policies (i.e. prescribed burning) may not be as significant as the Dept. of CALM model predicts.

**Surface Moisture Content**

Surface moisture content (SMC), also referred to as litter or fuel moisture content, indicates the flammability of fuels (Beck 1995). Decreased fuel moisture content increases the fire intensity, rate of spread and probability of a fire igniting (Catchpole et al. 2001; Catchpole 2002; Beck 1995).

The equilibrium moisture content (EMC) is the moisture content that the fuel will move toward under constant conditions (Viney 1991; Catchpole et al. 2001). It is governed by the local humidity and temperature, the fuel particle characteristics, and whether the particle is absorbing
or desorbing water (Viney 1991; Catchpole et al. 2001). As such it is a function of the meteorological condition of the forest. The equilibrium moisture content of a fuel is generally about 2% lower than for desorption conditions, being the afternoon drying phase (Viney 1991; Catchpole et al. 2001).

Equilibrium moisture content is generally modelled as a function of local relative humidity and temperature (Viney 1991; Catchpole et al. 2001). However, the estimation of SMC is confounded by the fact that fuel particles cannot respond immediately to changes in temperature and humidity. As such, actual SMC lags behind the predicted EMC. This lag is characterised by the ‘response time’. Since the move toward equilibrium is an exponential relationship with time, this response time is the time constant in the exponential decay. As such, the response time is the time it takes to accomplish approximately 63% of the movement toward equilibrium (Viney 1991; Catchpole 2002). Fine fuels, including jarrah litter, are often considered to have a response time of approximately one hour (Catchpole et al. 2001; Anderson 1990; Viney 1991).

Rain also has a significant effect on SMC. After rain, the larger fuels and deep layer of the litter bed retain moisture, reducing the amount of fuel available to burn (Catchpole 2002). This in turn reduces the intensity of a fire, as well as the rate of spread, depending on the study. Rainfall may also affect the fire regime in various time scales. That is, in the short term rainfall will change the surface moisture content, while in the longer term (weeks to months), drought periods may reduce the SMC of deeper or larger fuels. Alternatively, high rainfall in the months or years previous to the season of interest may increase the fuel load by allowing greater growth in the forest canopy (Luke & McArthur 1978; Ellis et al. 2004). The short term influence of rain on SMC has not been considered in this study, because of the difficulties in modelling its effect.

Soil moisture content has been shown to influence fuel moisture by its influence on local humidity (Hatton et al. 1988), however this influence is relatively small compared to the other factors mentioned, and will not be considered in this study.

**Wind and slope**

Wind and slope influence fire spread in similar ways. In each case the fire flames are bent in the direction of the fuel, whether upslope or downwind. The proximity of the flames to the unburned fuel increases the radiative heat transfer, which in turn increases the heating range and the rate of spread in that direction (Morandini et al. 2002).
Several studies have shown that a threshold wind speed exists, below which there is little fire spread (Burrows 1999a; Cheney et al. 1998). Above this threshold, fire spread rate increases at least linearly with wind speed. At high wind speeds, greater than linear increases in fire spread may be observed due to the effects of spotting, whereby burning material is propelled further than the fire front (Catchpole 2002).

Controlling variables

Studies conflict as to the relative importance of fuel load and weather variables. Jasper (1999) notes that in New South Wales, 95% of all fires which destroyed property occurred on days when fire danger was very high or extreme. This suggests that, in the case of extreme fires, weather variables are more controlling than fuel load. Similarly, simulations of intensity in western Canada attribute a minor role on fuel load when compared to weather (Bessie & Johnson 1995). This may be due to non-linear increases in intensity with FMC and wind, which then swamp the fuel load in extreme weather conditions.

However, numerous other studies have shown the opposite effect (Fernandes & Botelho 2003), and there are many observations of fires reducing in intensity on entering previously burnt areas (Underwood et al. 1985). It is unclear in the literature whether these studies concern less severe fires, where the effect of fuel load are more pronounced, or if the fuel/intensity relationship is, in fact, more complicated than previous believed. If this is the case, the effectiveness of fuel load reduction may vary by ecosystem and vegetation structure (Fernandes & Botelho 2003).

2.2.2 Fire spread and shape

When considering the effect of a fire on an asset, it is of interest to know how a fire is transported. Heat from a fire can be conveyed to its surrounding fuel or to an asset of interest by radiation, convection, direct flame contact, or any combination of these (Green 1983). The spread pattern of a fire is complicated by the local heterogeneity and variability of fuel load, surface moisture content and wind effects (Catchpole 2002). For example, SMC varies with altitude, rate of spread changes with slope, and wind is stronger on ridges and changes direction down valleys (Catchpole 2002). Both wind speed and moisture content vary throughout the day (Catchpole 2002), and therefore the life of a fire.

Despite the complexities, approximations as to the shape of a spreading fire may be made, particularly when spatial conditions are roughly homogeneous. Peet (1967) measured
experimental fire shapes and determined that an ovoid – an egg shaped variant on an ellipse – is the most accurate model for mild fire in Western Australian forest. While useful, it must be understood that this is a simplification of fire spread in heterogeneous conditions.

### 2.3 Fire modelling

#### 2.3.1 Approaches to modelling wildfire

Fire models are generally concerned with determining the rate of spread of a headfire under given conditions. Pastor et al. (2003) discusses the various approaches to the mathematical modelling of wildfire, where the approach may be classified as:

1. **Theoretical**: where a model is generated from the fluid mechanical, combustive and heat transfer laws that underpin the movement of fire.

2. **Empirical**: which are derived from statistical analyses of variables in experimental or known fire events.

3. **Semi-empirical**: which are proposed as theoretical expressions, but completed through experimentation.

Most theoretical models consider a one-dimensional theoretical fireline, represented by a flat fire front. Such models were especially popular during the initial development of fire modelling. However, the pragmatic interests of fire managers soon lead to a movement toward empirical solutions (Pastor et al. 2003). These are generally more accurate within the regions in which data has been collected, but cannot be applied outside of the region of interest (Pastor et al. 2003).

In this study an empirical model, the Forest Fire Behaviour Tables (FFBT), has been applied due to its development for the purposes of predicting fire spread in South West Western Australia. Currently in Western Australia, Project Vesta is being implemented to supersede the Forest Fire Behaviour Tables (Catchpole 2002). This is an empirical study which will investigate jarrah forest fires in more severe conditions than used in development of the FFBT, and investigate the effect of fuel load on fire behaviour (Catchpole 2002).
2.3.2 The Forest Fire Behaviour Tables

The Forest Fire Behaviour Tables (FFBT) are used by the Department of Conservation and Land Management (CALM) throughout the south-west of the state for predicting fire danger. These tables were derived from empirical data taken from experimental fires in the field, as well as some wildfire data (Beck 1995). Since this time, the tables have been converted to a series of equations by Beck (1995), to facilitate their use.

The tables use information about wind speed and surface moisture content to determine a headfire rate of spread for standard fuel conditions. This rate of spread is referred to as the Fire Danger Index, or FDI (Beck 1995). The FDI can then be corrected for non-standard fuel loads and slope to determine an actual rate of spread. In this study, slope will be assumed zero throughout, due to a lack of appropriate data.

The determination of surface moisture content in the Forest Fire Behaviour Tables requires a detailed understanding of the humidity and rainfall profiles of the previous day. The moisture content of the previous day is also required. A SMC for any given time is then calculated by estimating the drying of the fuel throughout the day by using the maximum temperature and minimum relative humidity (Beck 1995). This ‘bookkeeping’ procedure allows for an accurate estimate of surface moisture content by capturing the influence of seasonal and diurnal drying on fuel moisture (Beck 1995). However, the use of several non-standard measurements makes this model difficult to apply outside the operational structure of the Department of CALM. For example, the Overnight Relative Humidity Count is a required input, which is equal to the number of squares (of dimension 2% by two hours duration) under an overnight hygrograph trace, during which relative humidity exceeds 70% (Viney 1991). These difficulties limit the potential for use of the Forest Fire Behaviour Tables outside Dept. of CALM operations, and the tables have been simplified in their application in this study. This simplification is discussed in Section 4.4.2.

2.3.3 Fire spread models

The field of fire spread modelling has emerged in the past several years. These models consider the movement of a firefront through space, and the subsequent shape and properties of the fire, rather than just the rate of spread of the headfire. A simple and commonly applied approximation for the shape of a fire in homogeneous conditions is the ellipse, as proposed by Van Wagner (1969). The intensity of the firefront of this elliptical fire has been expressed by
Literature Review

Catchpole et al. (1982). This model is similar, but simpler to model than the ovoid, which has been suggested by Peet (1967) as the most appropriate for Australian conditions (see Section 2.2.2).

More complex models of fire behaviour exist, whereby fine-scale topographical and meteorological conditions are captured to model the fire spread over time. Examples of such systems include FIREMAP (Vasconcelos & Guertin 1992), SPREAD (Mendes-Lopes & Aguas 2000) and FARSITE (Finney 1998). Each of these systems uses topographical, vegetation and wind field data from a Geographical Information System (GIS) environment in order to model fire spread over a landscape. The most commonly applied model is FARSITE, which has been disseminated worldwide because of its adaptability to different vegetation types and its ease of use (Pastor et al. 2003). However, despite being at the forefront of fire spread modelling, FARSITE has not been thoroughly validated, and so inaccuracies in its simulations can be hard to identify (Pastor et al. 2003).

**Fire regime modelling**

Fire regime modelling involves modelling the characteristics of many fires over a long period of time, in order to capture the characteristics of the long-term fire regime. The more recent models are able to capture the regime over a real landscape, by the repeated application of the kind of fire spread models discussed above, yielding the intensity and fire spread characteristics of fires over time (McCarthy & Cary 2002). Detailed data regarding the spatial characteristics of the landscape (i.e. topography, vegetation, wind fields and temperature/humidity profiles over the seasons) is required for these models, as well as an estimate spatial distribution of and intervals between fire ignitions in the area (McCarthy & Cary 2002). There appears to be no reference in the literature as to the application of a return period analysis to these fire regimes, and this topic will be addressed further in this study.

### 2.4 Current management

#### 2.4.1 Prescribed burning / hazard reduction

The authority charged with fire management in the South-West Forest is the Department of Conservation and Land Management (Dept. of CALM). Fuel reduction burning is widely used by this authority as a fire protection technique in this region (Muller 1993).
The Department of CALM undertakes prescribed burning for three objectives:

a) To protect and conserve biodiversity values and community assets,

b) To reduce occurrence and impacts of large wildfires,

c) To regenerate and protect forest ecosystems following harvesting operations or other disturbances.

(Department of CALM 2003a)

This policy of fuel reduction has been in effect since 1954 (Underwood et al. 1985). The idea behind prescribed burning is to reduce fuel load in order to reduce the intensity of uncontrolled fires (Fernandes & Botelho 2003). While there are many variables contributing to fire intensity and spread (see Section 2.2.1), only fuel load can be mitigated against. In this sense, the policy is one of hazard management. The implementation of this policy involves the hand lighting of fires (Department of CALM 2003a), as well as “broad scale aerial burning” (Muller 1993), whereby incendiary devices are dropped from small aircraft. As of 2003, the 10 year average of area burnt in prescribed burning in South West W.A. was over 160,000 ha (Department of CALM 2003a). Prescribed burning has been reduced in Western Australia since the 1980’s due to reduced funding and the concern for smoke causing nuisance in metropolitan areas (Spriggins 2002; Muller 1993).

The benefits from hazard reduction can be observed conceptually in various fire models, which suggest the reduction of fuel load directly reduces fireline intensity. In particular, the Dept. of CALM’s Forest Fire Behaviour Tables predict greater than linear increases in intensity with fuel load (see Section 2.2.1). However, the operational effectiveness of prescribed burning is largely anecdotal (Cheney 1996; Fernandes & Botelho 2003), with most of the successful examples being in recently treated (less than 4 years) areas (Fernandes & Botelho 2003). Although there is anecdotal evidence that prescribed burning may reduce the spread of a major fire, these effects have not been properly quantified, particularly for high-intensity fires burning under extreme weather conditions (Fernandes & Botelho 2003). It is possible that other variables may be more important than fuel load under extreme weather conditions.
Section 2.2.1 (Controlling variables) of this report illustrates the conflicting evidence regarding the relative importance of fuel load and weather variables. It seems that the fuel/intensity relationship is not simple. Equally, conflicting statistical evidence regarding the effectiveness of prescribed burning complicates the argument over its use (Fernandes & Botelho 2003). Despite this, it is generally accepted that fuel reduction will reduce the fireline intensity of severe fires to some extent (Fernandes & Botelho 2003). This can benefit fire fighting operations by decreasing the required suppression forces, improving the safety of suppression personnel, or changing the suppression strategy, for example by allowing a direct attack rather than aerial suppression (Fernandes & Botelho 2003).

Prescribed burning aims to alter the fire regime to be dominated by frequent, low intensity burns, in order to exclude very intense fires. As discussed in Section 2.1.2, Australian flora and fauna are well-adapted to fire, and are able to survive or repopulate damaged areas. However, the frequent burning associated with a prescribed fire regime has the potential to alter the ecosystem by the mechanisms discussed in Section 2.1.2. Studies in the forests of eastern Tasmania suggest that fuel reduction burning has resulted in a simplified forest structure (Neyland & Askey-Doran 1996). Similar results have been found in the dry sclerophyll forests of central Victoria (Tolhurst 1996). Inappropriately frequent fire regimes have been implicated in the decline of 51 threatened bird species in Australia (Garnett 1992 as cited in; Keith et al. 2002), as well as in threatening 19 plant species with extinction (Leigh & Briggs 1992 as cited in; Keith et al. 2002).

Due to the complexities of ecosystem development, it is difficult to determine the degree to which prescribed burning affects the ecological structure of forests. Its effect will depend on the specific frequency and intensity regime applied, as well as the time taken for each of the many species in an area to recover. The resilience of Australian forest species to fire suggests that most fire regimes can be tolerated, although the longer term effects are harder to ascertain. Critics of prescribed burning question the necessity of burning whole-scale sections of the bush to effectively mitigate against wildfire, and whether this burning practice is damaging the affected ecologies (Cheney 1996). The different outcomes of prescribed burning on reducing large wildfire occurrence and on maintaining biodiversity illustrates the conflicting objectives which must be considered by the Department of CALM in fire management.
2.4.2 Wildfire Threat Analysis

The Wildfire Threat Analysis (WTA) is a decision support system currently employed by the Department of Conservation and Land Management for the support of fire management decisions (Muller 1993). The system involves the overlay of maps representing four categories of information: values at risk, the risk of ignition, the suppression response and the headfire behaviour.

Values at risk may include populated areas, property, threatened species, farmland or areas of scientific value. In the WTA, no effort is made to place a monetary value on each asset, and a zone is drawn around each asset within which a wildfire has the potential to cause damage (Muller 1993).

The risk of ignition map involves the identification of high, moderate and low ignition risk areas. Risk areas include those with high visitor use (with associated campfires or barbeques), those in the regular path of summer storms, and those with a recent history of ignition (for example from deliberate lightings) (Muller 1993).

The suppression response map reflects 3 aspects of suppression activity: the time until detection of a fire, the time it takes for suppression forces to reach the fire, and the time for an effective fireline surrounding the fire to be constructed. The measures of these times are relative only, and are represented by classes ranging from ‘Poor’ to ‘Immediate’. They are not intended to be a precise estimation of response or detection times (Muller 1993).

Finally, headfire behaviour is estimated by the use of the Forest Fire Behaviour Tables. These tables have been discussed in Section 2.3.2. For their use in the Wildfire Threat Analysis, a headfire rate of spread and intensity are calculated from fuel type and quantity, wind, slope and weather. Depending on the value of intensity and rate of spread, the headfire behaviour is nominated as one of five classes, which define the suppression responses which may be taken. These classes are:

<table>
<thead>
<tr>
<th>Headfire Behaviour Class</th>
<th>Intensity and Rate of Spread</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct attack on headfire front not possible</td>
<td>Intensity &gt; 3000 kW/m and/or ROS &gt; 800 m/hr</td>
</tr>
<tr>
<td>Ground attack on headfire not possible</td>
<td>Intensity 2000-3000 kW/m and/or ROS 400-800 m/hr</td>
</tr>
<tr>
<td>Machine attack possible</td>
<td>Intensity &lt; 2000 kW/m and/or ROS &lt; 400 m/hr</td>
</tr>
</tbody>
</table>
The value in the Wildfire Threat Analysis lies in the structured presentation of all factors that contribute to the wildfire risk. It provides a rational basis for decision making, and supports the clear and explicit explanation of the rationale behind fire management decisions (Muller 1993). While the WTA has value for fire management, the qualitative estimate of risk means that it is not possible to compare overall risk between any two areas, nor is it possible to develop a quantitative understanding of what that risk is. As such, the WTA has limited usefulness in the design and management of structures within risk areas.

### 2.4.3 Construction of buildings in bushfire prone areas

The Australian Standard 3959-1999, “Construction of buildings in bushfire prone areas”, is the design standard for construction in regions which have been designated as bushfire prone. The degree of protection required for a building is based on the local vegetation and slope characteristics, in an area of 350 m surrounding the site (Standards Australia 1999). For each category of bushfire protection – low, medium, high or extreme, a building construction level is selected for which there are specific guidelines. These guidelines include measures such as fire-retardant materials, insulation, tight fitting doors, and specific protection for roofs and ventilation (Standards Australia 1999).

This standard also uses a qualitative assessment of risk. This assessment uses local vegetative characteristics, rather than attempting to quantify the probability of an event. This is reasonable, given that the properties of the immediate surroundings will govern the risk of the building being damaged in the event of a fire. However, no consideration of the actual chance or expected intensity of a fire is given, other than the assessment of the area as ‘bushfire prone’. Presumably this assessment is not based on any kind of quantitative probability analysis. The design of such buildings could be better assessed by a complete determination of risk.

### 2.4.4 Risk Analysis

This study is formulated around a risk-based approach to wildfire management. A framework for the application of the Australian and New Zealand Standard for Risk Management (AS/NZS
4360:2004) to wildfire management was proposed by Nicol (2004 unpublished), and this framework will be presented in this section.

Since this proposal, the Council of Australian Governments National Inquiry on Bushfire Mitigation and Management (Ellis et al. 2004) has been published. This report confirms the approach proposed by Nicol, by emphasising that “a structured risk management process provides the most appropriate framework for formulating effective mitigation and management actions in relation to bushfires” (Ellis et al. 2004). The report continues, to remark:

> “the Inquiry considers that the Australian Risk Management Standard – AS/NZS 4360:1999 – should be applied in relation to bushfire by all relevant agencies in all jurisdictions” (Ellis et al. 2004)

### 2.4.5 Australian / New Zealand Standard 4360:2004

The Australian / New Zealand Risk Management Standard specifies a process for the management of risk, whereby risk is defined as ‘the chance of something happening which will impact on an objective’ (Standards Australia & Standards New Zealand 2004). Risk is measured as a combination of the likelihood (i.e. probability) of an event and its consequence. This definition of risk, which is applied in this study, implies the necessity of defining specific objectives. In the case of wildfires, these objectives would constitute assets which may include infrastructure, agriculture, property, human life or biodiversity.

The seven steps comprising the framework are outlined below:

1. **Establish the context**: establish the internal, external and risk management context in which the remainder of the process will take place. Criteria against which the risk will be evaluated should be established.

2. **Identify risks**: Identify where, when, why and how events could prevent, degrade, delay or enhance the achievement of the objectives.

3. **Analyse risks**: Evaluate existing control on risk. Determine the consequence and likelihood, and therefore the level of risk.
4. **Evaluate risks**: Compare the estimated levels of risk against the pre-established criteria (see step 1) and consider the balance between potential benefits and adverse outcomes. This enables decisions to be made about the extent and nature of treatments required and about priorities.

5. **Treat risks**: Develop and implement specific cost-effective strategies for increasing potential benefits and reducing potential costs.

6. **Monitor and review**: It is necessary to monitor the effectiveness of all steps in the risk management process. This is important for continuous improvement. Also, the risks and treatment strategies need to be continually monitored to ensure changing circumstances do not alter priorities.

7. **Communicate and consult**: Communicate and consult with appropriate stakeholders at each stage of the risk management process and concerning the process as a whole.

Steps 6 and 7 must be carried out continually during and after the process. The generic language of the Standard is obvious, and enables its application to a wide range of organizations and scenarios. Figure 2.1 is provided to help show the chronology of the process.
Figure 2.1: Overview of the risk management process. Source: AS/NZS 4360:2004

Application to wildfire management

The Council of Australian Governments’ Inquiry (Ellis et al. 2004), attempts to apply the Australian Risk Management Standard to the case of wildfire management. The model suggested is as follows:

1. *Establish the context:* Identify assets, their location and the particular objective relating to each from the perspective of the groups which gain a benefit or value from the asset. Risk evaluation criteria can relate to economic impact, health impact, loss of biodiversity, infrastructure damage or the loss of cultural and heritage value. An understanding must be developed of current management and strategic plans, relevant legislation and government policies, and key biological, physical, social and economic data.

2. *Identify risks:* Investigate the characteristics of the hazard for the domain, in particular the factors contributing to the likelihood of ignition and the consequential progress of a bushfire. Specifically, this refers to fuel and weather conditions. Identify key characteristics of the community and the environmental (built, natural and social) to determine the vulnerability of each asset.
3. **Analyse risks**: Determine the likelihood of a bushfire event using historical information and data and past experience and determine the probable consequences or impacts of a fire for the set of identified assets and values.

4. **Evaluate risks**: Compare the levels of risk determined during the analysis and develop priorities for further action. As part of this evaluation, assess how risks will change under various treatment options.

5. **Treat risks**: Select and implement treatment strategies to reduce the likelihood of harm to assets and values. These may avoid the risk (e.g. land use regulations), reduce the risk (e.g. building regulations, fuel reduction activities), spread the risk (e.g. share readiness responsibility between various fire agencies and residents) and manage the risk (e.g. effective fire-suppression plans, community readiness).

The subject of this report primarily concerns steps 2 and 3, with the objective of quantifying the risk of an event, in order to better understand and treat the factors influencing risk.

**2.4.6 Environmental Risk Management**

An Environmental Risk Management Scheme has been proposed by Steedman and Goff (1997). This process applies the Australian and New Zealand Risk Management Standard AS/NZS 4360:1995, as well as the International Standard ISO/NWI 14140 risk standard. The ISO standard defines risk as the ‘combination of the chance that a specified undesired event will occur and the severity of the consequences of the event’. This definition is limited because it does not allow for the definition of assets and objectives as in the Australian and New Zealand Standard, and so does not adequately deal with the management and control of risk (Goff & Steedman 1997). However, it does allow for a more precise quantification of risk, whereby risk is separated into four independent categories (Goff & Steedman 1997):

1. **Primary risk**: the probability of an undesirable event occurring

2. **Secondary risk**: the probability of the consequences of an event reaching an asset of value given that the event has occurred.
3. **Tertiary risk**: the probability of an event causing damage given that the consequence of the event reached an asset of value; and

4. **Quaternary risk**: the probability that an area damaged by an undesirable event can recover from the impact given that it has been damaged.

Because the four categories of risk are independent, a total probability of an event occurring and causing damage can be obtained simply by multiplying the probabilities. The advantage of such a model is that the individual probabilities may be assessed to determine the most important sources of risk, and the risk can be mitigated appropriately and efficiently (Goff & Steedman 1997).

**Application to wildfire management**

Nicol (2004 unpublished), suggested the application of Steedman and Goff’s proposed scheme to the problem of wildfire risk. Primary, secondary, tertiary and quaternary risks were defined as follows:

1. **Primary risk**: the probability of a fire igniting in a given area

2. **Secondary risk**: the probability of a fire moving throughout the landscape and reaching a valuable asset, such as a town or area or biodiversity.

3. **Tertiary risk**: the probability of an event causing damage to the asset, given that it reaches that asset

4. **Quaternary risk**: the probability that an area damaged by a wildfire event can recover, given that the damage has occurred.

Steedman and Goff’s Environmental Risk Management framework and the Australian Risk Management Standard are not mutually exclusive. In fact, the idea of independent risk complements the Standards’ steps of analyzing and evaluating risks, with the advantages discussed in Section 2.4.7.

The advantage of using independent probabilities has been realized in a similar framework applied elsewhere in fire management. Preisler et al. (2004) developed a probability based
model for estimating fire risk, where risk is defined using three independent probabilities. The first is the probability of a fire occurring, the second is the conditional probability of a large fire given ignition. The third probability is the product of the first two, which represents the unconditional probability of a large fire event. This framework was developed to allow the assessment of contributing variables (such as weather and fuel) to fire risk (Preisler et al. 2004).

2.4.7 Advantages of a risk management framework

The application of a risk management framework provides significant advantages over a policy of simple hazard management. The framework provides a transparent, auditable process which allows for objective and informed decision making (Standards Australia & Standards New Zealand 2004).

The definition of specific objectives (i.e. protection of assets, biodiversity etc), is a significant improvement over hazard management, where insufficient consideration is given to the specific assets which are in need of protection. Even while such considerations may be implemented pragmatically by fire managers, a hazard management approach does not provide sufficient framework for its widespread and accountable application.

The application of a risk management framework requires knowledge of the likelihood of damage to an asset. Preferably, this knowledge is quantified in terms of a probability, rather than a qualitative or relative likelihood. Relevant data is required for the application of the risk management framework, and as such, management can be improved by an analysis of past events (Ellis et al. 2004). Research can provide valuable insight into the relationships and influence of critical factors (Ellis et al. 2004). It is in these analyses that the work in this study is able to contribute to the risk management process.

The adoption of the Wildfire Threat Analysis represents a move by the Department of CALM toward a more structured management process. It has been noted that almost all aspects of the WTA involve a qualitative assessment of risk. Preferably, these probabilities that are expressed qualitatively in the WTA may be quantified to provide a more concrete understanding of risk within a complete risk management framework.
2.4.8 Return period analysis

Return period analysis is used in this study to quantify the likelihood of a fire event of some specified intensity being exceeded. This method is most commonly used in flood frequency analysis, where it is used to estimate the probability of a flood of a given magnitude occurring within some time frame, usually one year (Pilgrim 1997). This method is common in engineering design, and has been applied to other fields, such as to estimate ocean wave heights (Petrauskas & Aagaard 1971) and sewer overflows in urban storm water management (Grum & Aalderink 1999).
3 Background

3.1 Study site

3.1.1 Physical context

This study concerns itself with the area designated as and surrounding the Jarrah Forest of south-west Western Australia. Jarrah forest is the general description given to forested areas in south-west W.A. in which the dominant tree species in jarrah or a mix of jarrah (*Eucalyptus marginata*) and marri (*Eucalyptus calophylla*) (Burrows et al. 1999). The study includes the areas surrounding the Jarrah Forest because fire data exists for these areas, even though many assets of interests (e.g. townships) lie outside the strict bounds of the forest (CALM unpublished data).

The region experiences a Mediterranean-type climate, which is characterised by cool wet winters and hot dry summers (Burrows et al. 1999). The average annual rainfall across the range of the forest varies from 650 mm to 1300 mm per annum, of which approximately 80% falls over winter (Burrows et al. 1999). The average number of days in which the forest fuel is dry enough to sustain a wildfire varies from 140 to 160 across the region (Burrows et al. 1999). Blow-up days, which represent the worst fire conditions, occur once or twice each summer (Underwood & Christensen 1981). These are characterised by heatwave conditions with strong, dry winds from the interior, and vegetation becomes extremely dry and easily ignites (Underwood & Christensen 1981). These days have been associated with all the worst forest fires in Western Australia (Underwood & Christensen 1981).

Fuel load varies across the forest. The fuel age is largely defined by the prescribed burning policy, which has been in place since 1954 (Underwood et al. 1985). A burning rotation of 5-15 years (Department of CALM 2003b) is applied to the forest, with the aim of keeping fuel load below 6-8 tonnes/ha (Peet 1965). A map of the fuel load within the Jarrah Forest, as well as its extent, is shown in Figure 3.1, below:
Population centres exist throughout the forest. The Perth suburban area is skirted by forest to the north and east. Assets in the region requiring management or mitigation from wildfires include threatened species, farmland, towns, rural estates and infrastructure (Muller 1993).

3.1.2 Sources of ignition

Data for the 2002/2003 fire season (Ellis et al. 2004) as well as unpublished data from the Department of CALM suggest that approximately 45% of fires are started deliberately. Approximately 27% of fires were started from accidental causes, including escapes from burn off and recreational and industry accidents (Dept. of CALM unpublished data).

3.2 Previous work

This study follows on from another dissertation by Samuel Nicol, in 2004 (unpublished). The previous study involved the application of seventeen years of fire data from the Department of CALM to develop an intensity verus return period relationship for fires in the South-West of Western Australia. Since this study builds on the previous work, many of the same methods and data are employed. However, the previous study had several significant deficiencies:
1. The simulation used to develop the intensity-return period relationship was based on FDI data, rather than the source variables which actually contribute to this index. This has two major disadvantages. Firstly, the individual weather parameters cannot be analysed to determine their importance. Secondly, the model cannot be applied to areas outside South-West WA, where a dataset of FDI may be unavailable.

2. Because the individual weather parameters were not provided in CALM’s dataset, a uniform distribution of fuel moisture content was applied to determine each fire’s rate of spread. This distribution is not based on any actual observation, and is almost certainly insufficient.

3. The intensity-return period relationship which was developed did not include any spatial information, and so applies to the entire South-West forest region. That is, for any intensity fire, the associated probability was of a fire event of that intensity occurring anywhere within the forest. While this provides a useful model for a sensitivity analysis of the variables contributing the fire behaviour, it is not useful for predicting the probability of a fire occurring in the vicinity of an asset of interest. Such a model is of limited usefulness for the quantification of risk in a risk management framework.
4 Methods

4.1 Overview

This study applies return period analysis to the problem of wildfires in Western Australia. This involves the calculation of intensity for specified return periods of wildfires. Fire data and weather data were taken from the Department of Conservation and Land Management, and the Bureau of Meteorology respectively. These were used to determine probability distribution functions of:

a) The number of fires per year;

b) The average number of fires in each month of the year

c) Afternoon humidity, temperature and wind speed for each month of the year; and

d) Spatial occurrence of ignitions

Using the formulae for the Forest Fire Behaviour Tables in conjunction with a Monte Carlo analysis, a return period distribution of the Fire Danger Index was determined for the entire forest. That is, some number of fires were considered to occur over the forest, and their conditions were modelled. No regard was given to their place of occurrence and so no spatial information was included.

This distribution is similar to that developed in the previous study, referred to in Section 3.2. However, it has been developed to address the shortcomings which have been discussed, by calculating the Fire Danger Index from the source weather variables, instead of using a distribution of FDI.

The forest has been broken into a 10-by-10 km grid, and the FDI relationship has been scaled to the smaller areas, depending on ignition frequency. Finally, expected intensities are calculated using the fuel load for each grid area.
4.2 Data

Seventeen years of complete fire data was obtained from the Department of CALM. This data included the date and time of detection, the position of the fire, the cause of the fire and the total area burnt. There were some spurious entries in this dataset, with some fire locations obviously being incorrectly listed, for example, a handful of fires were located in the Indian Ocean. The possibility of data errors with regard to position was confirmed with the Department of CALM and these locations were removed from the dataset.

Daily 3 pm values of temperature (°C) and relative humidity (%) were obtained from the Bureau of Meteorology, for various stations scattered throughout the forest, and for a one-year period between November 2003 and October 2004. While daily 3 pm data does not provide complete resolution of weather conditions, it does allow for a conservative estimate for intensity, with the highest wind and lowest surface moisture content usually seen at mid-afternoon (Catchpole 2002). A minimum SMC and an afternoon wind speed are often used to find a maximum Fire Danger Index for the day (Beck 1995). Also, the distribution of times at which fires occur (Dept CALM unpublished data) suggests that the incidence of fire ignitions peak in the early afternoon. Year-long data has been taken from meteorological stations at Dwellingup, Jarrahwood and Pearce. It is assumed that the distributions determined from this single year reasonably represent all years.

Fuel load, expressed as the number of years since the last burn, was obtained from the Department of CALM for those regions designated as Northern Jarrah Forest, as at the end of 2003. Fuel load is not constant with time, as it changes with the annual leaf fall and burning regime, however for the purposes of this study only fuel load at the present time is required. The 2003 data will suffice for the purpose of examination.

The fuel load data is converted into tonnes/ha, which is required in the Forest Fire Behaviour Tables, by the formula (Beck 1995):

\[
AFQ = (0.18CC + 11.06)(1 - \exp\{-0.086YSLF\})
\]

Where:
Methods

\[
\begin{align*}
\text{YSLF} &= \text{The number of years since the last fire} \\
\text{CC} &= \text{Forest canopy cover (\%)}
\end{align*}
\]

In this study, the canopy cover has been arbitrarily set at 50\% for the entire forest, due to a lack of information otherwise. This may be revised in further work if more information is available.

Many of the ignition locations given in the Department of CALM dataset lay outside the boundaries of the Northern Jarrah Forest. Since these areas were still of interest, often representing the urban-forest fringe, a value of 1 t/ha was chosen arbitrarily to represent the fuel load outside of the strict bounds of the Northern Jarrah Forest. Further investigation of fuel loading in these areas of interest is required to improve the dataset.

4.3 Probability Distribution Functions

For the purposes of Monte Carlo simulation, it is necessary to have the governing variables expressed as random variables belonging to certain specified probability distributions. Consequently, probability distribution functions were fitted for the number of fires per year, temperature, humidity, wind speed and the area of ignition.

4.3.1 Number of fires per year

A Poisson distribution has been used to model the number of fires which occur in each year, with a burnt area greater than 10 ha. The 10 ha limit has been applied so that the distribution includes only those fires which successfully ignite and spread. The Poisson probability distribution is given by:

\[
p(x) = \frac{\lambda^x e^{-\lambda}}{x!}
\]

where \(x\) is the value for which the probability, \(p(x)\), is estimated, and \(\lambda\) is the expected value (Dowdy & Wearden 1983; Yevjevich 1972). The distribution is entirely described by this parameter (Dowdy & Wearden 1983; Yevjevich 1972). This probability distribution function is converted to a cumulative distribution function so that a unique probability exists for each value in the distribution.
The application of the Poisson distribution makes the following assumptions, in keeping with the properties of a Poisson distribution:

1. The probability of a fire occurring at any point in time is very small and constant.

2. Within a sufficiently small time frame, the probability of two fires occurring is negligible.

3. The occurrence of one fire does not have an effect on other fire events. That is, the occurrence of events is independent.

The assumption that each fire event is independent may be questioned. A fire reduces the fuel load of the area in which it burns. This may, in turn, reduce the probability or intensity of a fire occurring in the same area at some future time.

4.3.2 Temperature, humidity and wind speed

The daily values of temperature, humidity and wind speed from all locations have been amalgamated. Probability distribution functions for these variables are then produced for each month of the year, given that these weather variables can vary significantly depending on the season. Due to the amalgamation of data from all locations, the PDFs represent weather variables over the entire forest.

The 2-parameter Gamma distribution is used to model the weather variables. This distribution is more versatile than the Poisson, and was observed to better capture the range of values within each month. The Gamma distribution is given by:

\[
\begin{align*}
    f(x; \sigma, \lambda) &= \frac{1}{\sigma \Gamma(\lambda)} \left( \frac{x}{\sigma} \right)^{\lambda-1} \exp\left( -\frac{x}{\sigma} \right)
\end{align*}
\]

Where the Gamma function is defined as:

\[
\Gamma(\lambda) = \int_0^\infty x^{\lambda-1} \exp\{-x\} dx
\]
The parameters of the distribution, $\lambda$ and $\sigma$, are estimated within MatLab by a maximum likelihood estimation. This process involves using the input data to calculate the most likely values of the parameters as well as confidence intervals for each.

In Bureau of Meteorology data, the wind speed is measured at a height of 10 m. This must be altered to a fuel height of 1.5 m for application in the Forest Fire Behaviour Tables. This is done by the formula (Viney 1992):

Equation 4.5: Equations for reduction of wind speed to fuel height level

$$u_f = u_z \ln\left(\frac{h_0 - d}{z_0}\right) / \ln\left(\frac{z - d}{z_0}\right)$$

$$d = \frac{2}{3} h_0$$

$$z_0 = 0.13 h_0$$

Where:

- $u_z$ = Wind speed at the measurement height (10 m)
- $u_f$ = Wind speed at the fuel height
- $h_0$ = Fuel height (1.5 m)

### 4.3.3 Month of occurrence

A probability distribution function exists for each of the weather variables for each month of the year. In order to select which PDF is to be sampled from, the month of occurrence of each fire event must be determined. For this purpose, a probability mass function of the month of ignition was determined from the fire data.

### 4.3.4 Probability of ignition in an area

The location at which a fire occurs is important when estimating intensities for individual grid areas. In this study, the probability of a fire occurring within an area is assumed to be related to the frequency of past events. The positions of all the events in the dataset are plotted, and the number of events is summed within each grid area. The summations are then normalised by dividing by the total number of events to give a probability distribution. Note that this is not the
probability of a fire event occurring in the area, but the probability of it occurring in the area, given an event occurs.

There are several assumptions in this process. Firstly, that the position of future fire events is related to the position of past events. Ignitions tend to consistently occur around populated areas and roadways in the case of accidental and deliberate ignition, and within storm belts (Chris Muller 2004 personal communication), making this a reasonable assumption.

The second, and most important, assumption is that each fire event exists only within the grid area of interest. This study assumes that the probability of ignition in an area is equivalent to the probability that a fire will affect that area. In this way, the extent of each fire event is not considered. This is partly because of the shortcomings in fire area data in the Dept. of CALM’s dataset, and also because of the difficulties in predicting the area of a wildfire, requiring information concerning local scale variations in fuel and the availability of suppression resources. In reality, transport processes may allow fires which ignite in one area to move into an adjacent area.

4.4 The Forest Fire Behaviour Tables (FFBT)

The Forest Fire Behaviour Tables, as described in Section 2.3.2, is the fireline intensity model used in this study. The FFBT uses input of weather and fuel variables to determine a rate of spread of the fireline. The method employed in this study involves a modification of the FFBT, whereby the process for calculating surface moisture content is simplified as described in Section 4.4.2. For clarification of the process, Figure 4.1 illustrates the overall method for calculation of fireline intensity. The dotted line describes the point at which distributions of SMC and FDI are scaled down according to the area in question.
Figure 4.1: Process for calculation of fireline intensity. The dotted line shows where the FDI and SMC distributions are scaled down for a smaller area.

For each fire event to be modelled, the month in which the fire occurs is chosen from the probability distribution function of the month of occurrence. This defines the PDFs which are used to choose wind speed, temperature and humidity. The temperature and humidity are used to calculate the surface moisture content, as described in Section 4.4.2. The Fire Danger Index is then calculated by the equations:

Equation 4.6: Fire Danger Index Equation

\[ FDI = Y_j + A_j \exp(WIND \times N_j) \]

With:

\[ Y_j = 21.37 - 3.42SMC + 0.085SMC^2 \]

\[ A_j = 48.09SMC \exp(-0.60SMC) + 11.90 \]

\[ N_j = -0.0096SMC^{1.05} + 0.44 \]

where:

- \( SMC \) = Surface Moisture Content (\%)
- \( WIND \) = Wind speed (km\( h^{-1} \)) at a height of 1-2 m above the ground
This Fire Danger Index represents the rate of headfire spread for standard conditions, being on level ground and with a fuel load of 8 tonnes/ha (Beck 1995). To correct for non-standard fuels, a Fuel Quantity Correction Factor (FQCF) is calculated, based on the fuel load and surface moisture content. The FQCF is determined by a set of four functions, each with specific application bounds (Beck 1995). These equations are:

\[
F_{QCF} = \frac{1.02}{1 + 7266.83 \exp(-1.36AFQ)} + 0.10 \\
\quad \text{2.5 < AFQ < 8.0} \\
= 6.03 + 5.81AFQ \\
\quad \text{8.1 < AFQ < 25.0} \\
= \frac{11.19 + 2.92AFQ}{35.02} \\
\quad \text{8.1 < AFQ < 25.0} \\
= \frac{0.055 + 0.0023AFQ}{0.074} \\
\quad \text{8.1 < AFQ < 25.0} \\
\]

\[
\]

In these equations, the available fuel quantity (AFQ), or fuel load, is expressed in tonnes/ha.

Finally, the rate of spread, corrected for non-standard fuel load, is given by:

\[
\text{Equation 4.8: Fuel corrected rate of spread} \\
ROS = F_{QCF} \times FDI
\]

4.4.1 Calculation of fireline intensity

The intensity of a fire can be calculated from the rate of spread and fuel load, using the equation (Byram 1959; in Catchpole 2002):

\[
\text{Equation 4.9: Fireline Intensity Equation} \\
I = HwR
\]

where:

\[
\begin{align*}
I &= \text{Intensity (kW/m)} \\
H &= \text{Heat of combustion (KJ/kg)} \\
w &= \text{Fuel weight per unit area (kg/m}^2) \\
R &= \text{Headfire rate of spread (m/s)}
\end{align*}
\]
This represents the heat release rate per unit fire-line length. A value for $H$ of 16,920 kJ/kg is suggested for Australian fuels (Muller 1993), and using units corresponding with CALM data records, the equation reduces to:

**Equation 4.10: Fireline Intensity Equation (modified units)**

$$I = 0.47wR$$

where:

- $I$ = Intensity (kW/m)
- $w$ = Fuel weight per unit area (tonnes/ha)
- $R$ = Headfire rate of spread (m/hr)

### 4.4.2 Surface moisture content calculation

In the Forest Fire Behaviour Tables, the calculation of surface moisture content is more complicated than the method used in this study. Two factors in particular make the use of the Forest Fire Behaviour Tables’ surface moisture content calculations difficult for this analysis. Firstly, records of Overnight Relative Humidity Count are not readily available, as they are calculated at each CALM district office in the forest area and are either not kept or kept only in written form (Chris Muller 2004 personal communication). Secondly, the method employed in the FFBT is a ‘bookkeeping’ method, in which today’s SMC is calculated using yesterday’s SMC. This makes it impossible to develop a probability distribution of surface moisture content.

Due to these complications, an alternative method for SMC calculation has been used. A discussion of available models to calculate the moisture content of forest fuels is given in Viney (1991) and Viney (1992). From the available models, the McArthur (1967) model has been chosen. This comprises part of the Forest Fire Danger Meter, which is used extensively in Eastern Australia, and was developed from the tabulation of moisture content data from *Eucalyptus* litter (Viney 1992). The equation for this model is:

**Equation 4.11: McArthur’s (1967) model for Surface Moisture Content**

$$SMC = 5.658 + 0.04651H + 3.151 \times 10^{-4} \frac{H^3}{T} - 0.1854T^{0.77}$$

Where:
H = Relative Humidity (%) \ (5 \leq H \leq 70) \\
T = Temperature (^\circ C) \ (10 \leq T \leq 41)

This model was selected due to its relevance for application to Australian vegetation, and its compatibility with the methods in this study.

4.5 Monte Carlo Simulation

Monte-Carlo simulation refers to any process which uses the repeated random sampling from the probability distributions of the relevant random variables to simulate a process (Koller 2000; Manno 1999; Sobol 1974). Calculations are carried out by using inputs from probability distributions which approximate the real variation in conditions (Koller 2000; Manno 1999). Then deterministic equations can be applied to calculate an output from the random input variables (Koller 2000). In this way a random input is combined with a deterministic model to develop a corresponding stochastic output. This technique is useful in risk analysis because it involves the integration of several random variables to develop a probability distribution of the output of interest (Koller 2000), in this case fire intensity. Generally in a Monte Carlo analysis, variables are selected independently from their probability distribution functions, requiring that the input variables must be independent (Koller 2000). When there is interdependence between input variables, joint distributions should be determined to ensure that the input variables are properly correlated.

In the case of this study, input variables of weather conditions are described by probability distribution functions. These are sampled and intensities are derived by the use of the Forest Fire Behaviour Tables. These intensities then correspond to the input distributions which have been sampled.

100 years of fire events have been modelled using Monte Carlo simulation. The numbers of fire events in a year are selected from the probability distribution function of annual number of events. For each event, a month of occurrence and subsequent wind speed, temperature and humidity are selected from their respective PDFs. The Forest Fire Behaviour Tables are applied to determine the SMC and FDI of each fire event. At this stage, the fires are modelled for the entire forest domain. Intensity cannot yet be calculated because the fuel load is specific to each grid square of interest.
4.6 Return Period Analysis

The return period (T) of an event with a given magnitude is defined as the average time between events which are equal to or exceed that magnitude (Bedient & Huber 1992). The reciprocal of the return period is the probability of exceedance of the event (Bedient & Huber 1992). This concept is powerful in the context of this study in that it represents the likelihood of an event, in keeping with the objectives of a risk analysis. It is important to note the return period represents a probability of exceedance in any year, and does not indicate a defined time between events.

Return periods are calculated from the annual maximum series. This is the set comprising the largest event from each year (Bedient & Huber 1992). The largest event in one year is assumed to be independent of the largest event in any other year (Bedient & Huber 1992; Pilgrim 1997). To calculate the return period of each event in the annual maximum series, the events are ranked from greatest intensity to smallest, and the following formula is applied (Pilgrim 1997):

\[
T = \frac{M + 1}{n}
\]

Equation 4.12: Return Period Calculation (Pilgrim 1997)

where:

- \( T \) = Return Period (years)
- \( M \) = total number of years in record
- \( n \) = Ranking of the fire in the distribution

In this study, the Monte Carlo simulation generates 100 years of fire events, represented by their Fire Danger Index, and the largest was chosen from each year to develop the annual maximum series. Equation 4.12 was applied to generate a Fire Danger Index – return period relationship.

Due to the randomness inherent in a Monte Carlo simulation, the process of simulation and the generation of the FDI – return period relation was run 50 times. The subsequent distributions were averaged to give a final distribution of FDI to return period. Repeating the simulation more than 50 times was found to result in little difference to the mean. As an alternative to the mean, the median of the distributions may be chosen as the measure of central tendency. This approach is often used in flood frequency analysis (Pilgrim 1997). Similarly, if the most conservative
estimate is desired, the maximum values may be chosen. The decision as to which measure to use is largely subjective.

This FDI return period distribution represents a distribution of expected fireline rate of spread under standard fuel conditions, over the entire forest. Each value of the Fire Danger Index in the distribution has a surface moisture content value associated with it, so that intensity may be calculated.

4.7 Spatial Scaling

4.7.1 Scaling mechanism

The number of fires which occur within each grid area within the forest is smaller than the number occurring in the entire forest. To account for this fact, the FDI return period distribution must be scaled down appropriately for each smaller area. The scaling mechanism is based on the reasoning that a smaller number of events will be expected in any smaller area than the total forest, and that the corresponding Fire Danger Index distribution is that which is created by reducing the number of expected events in that area. For example, if 10% of all fires are expected in a chosen area of the forest, then the FDI distribution is created from the same Monte Carlo simulation as used previously, but where the expected number of events is multiplied by 0.1. The FDI return period distribution for any given proportion of events can be expressed as:

\[ FDI_p(T) \]

where a distribution exists for any proportion of events, \( p \), and the Fire Danger Index is a function of the return period, \( T \). The FDI return period distribution for the entire forest is therefore given as \( FDI_1(T) \). Return period distributions of FDI have been calculated for proportions of \( p = 1, 0.8, 0.6, 0.4, 0.2, 0.1, 0.05 \) and \( 0.03 \). Below a proportion of 0.03 the simulation fails, as a sampling error occurs whereby no fires are found in a year. It is this regime that is of interest, since the proportion of total events which occurs in each grid square is generally less than 0.03 (see Figure 5.13b). In order to move into the regime below 0.03, the relationship between the magnitude of the FDI distribution and the proportion of events \( (p) \) needs to be determined. That is:

\[ FDI_p(T) = R(p,T)FDI_1(T) \]
with $R(p, T)$ the ratio between the FDI distribution with proportion of events, $p$, and the distribution for the entire forest. $R$ will vary with return period, but this dependence is ignored, and values of $R$ for each modelled value of $p$ may be determined by taking the average of the ratio of the two distributions. That is:

$$R(p) = \text{mean} \left( \frac{\text{FDI}_p(T)}{\text{FDI}_i(T)} \right)$$

This gives the function $R(p)$ in the interval $(0.03, 1)$. This relationship was then plotted and extrapolated linearly to determine the ratio below $p = 0.03$. Therefore Equation 4.13, below, may be used to determine the FDI return period distribution for any given value of $p$, including when $p$ is less than 0.03.

Equation 4.13: FDI return period distribution for an area as a function of $p$ and the distribution for the entire forest

$$\text{FDI}_p(T) = R(p)\text{FDI}_i(T)$$

where $R(p)$ is now known.

An identical process was carried out for the surface moisture content. In the case of the FDI, a boundary condition was applied which stated that $R(p)$ equalled zero when $p$ equalled zero. This boundary condition was arrived at intuitively, knowing that if the probability of a fire event occurring within an area of interest is zero, then the expected intensity (and therefore FDI) will also be zero.

Return period distributions of FDI and SMC can now be found for any area, if the number of events which are expected in this area, relative to the total number in the forest is known. The return period distributions may be found for each grid square, since the expected proportion of events in each area corresponds to the spatial probability distribution function of fire ignitions (see Section 4.3.4). This method can be applied to any smaller region of interest, and is not confined to use in a grid structure.
4.7.2 **Intensity Calculation**

Scaled FDI and SMC return period distributions are determined for each grid square in the forest. The fireline intensity is then calculated by using the known fuel load for each grid square. This is done by calculating a Fuel Quantity Correction Factor and headfire rate of spread by Equation 4.7, Equation 4.8 and Equation 4.10.

This gives a *fire frequency distribution*, being the relationship between intensity and return period, for each grid area in the domain. This is a quantification of risk. For any return period, $T$, and within any grid area, the fireline intensity which will be exceeded on average once every $T$ years can be calculated. This is presented as a map of intensity in each grid area for any return period.

4.8 **Additional Analysis**

4.8.1 **FDI distributions**

For the purpose of calibration, distributions of FDI have been formulated both from the Dept. of CALM dataset and from the Monte Carlo simulation, which uses probability distribution functions of weather variables. These distributions apply to the entire forest.

4.8.2 **Independence of weather variables**

The values of wind speed, temperature and humidity which were used to create probability distribution functions were plotted against one another in order to ascertain their independence. This was done for the original weather variables and for those sampled from the probability distributions. Correlation coefficients were calculated for each plot.

4.8.3 **Controlling variables**

Scatter plots were created for intensity vs. fuel load and intensity vs. probability of ignition, using values corresponding to each grid area in the spatial intensity map. The correlation between these variables is an indication of which variables control the expected intensity.

4.8.4 **Sensitivity to spatial variables**

The three factors influencing risk in this study are aggregated weather conditions (giving FDI, equivalent to the rate of spread), fuel load and the probability of a fire occurring in some area.
Full ranges of the values of each of these factors were altered independently to gain the relationship of intensity with their variation.

### 4.9 Fire Area Modelling

The methods presented here aim to show the potential for the use of fire spread modelling for estimating risk. A simplified fire spread model is presented, along with the calculation of its effect on an asset. In this way, it can be shown that the spatial transport mechanisms of a simple fire in homogeneous conditions may be captured in the risk analysis.

A diagram of the elliptical fire front model which is considered in Van Wager (1969) and Catchpole et al. (1982) is shown in Figure 4.2, below.

![Elliptical fire front model](image)

**Figure 4.2: Elliptical fire front model, and the quantities which describe it. Diagram modified from Catchpole et al. (1982)**

The fire is driven in the x-direction by wind. The position and shape of the fire front is defined by the rate of spread of the fire under zero-wind conditions \( R_0 \), and the coefficients \( g \), \( f \) and \( h \). These coefficients define the shape of the ellipse, and are governed by the wind speed (Finney 1998). The derivation of the formulae in this section will not be presented, but a complete derivation and discussion of all formulae is given in Appendix A.

The intensity at any point on this fireline is given by Equation 4.14:
Equation 4.14: Intensity at any point on an elliptical fire front (Catchpole et al. 1982).

\[
I = \frac{Hw(R_h g \cos(\theta) + f)}{\sqrt{h^2 \cos^2(\theta) + f^2 \sin^2(\theta)}}
\]

where:

- **I** = Intensity (kW/m)
- **H** = Heat of combustion (KJ/kg)
- **w** = Fuel weight per unit area (kg/m²)

and **R₀, h, g, f** and **θ** are defined in Figure 4.2.

The point O(x₀, y₀) in Figure 4.2 is a point corresponding to an asset of interest. The heat experienced by this point will be due to the combined radiated energy from the entire length of the fireline. While the heat from a fire is transported both by convection (in the vertical direction) and radiation (in all directions) (Luke & McArthur 1978), it is assumed in this model that all heat is transferred by radiation. Also, it is assumed that there is no interference of the radiation by matter between the source and the object. By considering the power at the point O due to the heat output from any point on the fireline, and integrating over the entire ellipse, the total power experienced at O due to the fire at any time, \( t \), is given by Equation 4.15:

**Equation 4.15: The total power experienced at a point of asset, due to an elliptical fire**

\[
P_{O,Total} = 0.47wR_0h^2 \int_0^{2\pi} \left[ (g \cos(\theta) + f) f \left[ 1 - (1 - \frac{h^2}{f^2}) \sin^2(\theta) \right]^{1/2} \right] \delta\theta
\]

where \((x₀, y₀)\) are the coordinates of the point O relative to the point of ignition of the fire. The power is measured in kilowatts (kW).

Equation 4.15 has been applied to show the power experienced at a point over time due to a fire passing nearby. The constants used to define the fire in this analysis are:

- **f** = 2
- **g** = 1.8
\begin{align*}
h &= 1 \\
R_0 &= 10 \text{ m/hr} \\
w &= 6 \text{ tonnes/ha}
\end{align*}

$R_0$ and $w$ have been chosen arbitrarily. The values of $f$, $g$ and $h$ are given in Catchpole et al. (1982) as typical coefficients for a fire in a medium wind.
5 Results

5.1 Return Period Analysis

5.1.1 Number of ignitions per year

Figure 5.1 shows the number of fires with an area greater than 10 ha which have occurred in each year of the fire record. These values have been used to create the cumulative distribution function seen in Figure 5.2. This is the relationship which is used to randomly model the number of fires which occur in each year.

![Figure 5.1: Number fires greater than 10ha in each year of the fire record](image)

Figure 5.2 suggests that between approximately 30 and 50 fires with a burnt area greater than 10ha will occur in the forest each year. The mean value is 40.33 fires. The probability mass
function of the month in which a fire occurs is shown in Figure 5.3. The highest probabilities are in the summer months, where high air temperatures and low surface moisture content leave fuel highly flammable and able to ignite. Almost no fires occur during winter (June, July and August), where fuel moisture is too high to sustain a burn.

Figure 5.3: Probability Distribution Function of month in which a fire event will occur

5.1.2 Weather variables
Figure 5.4 (a, b & c): Monthly cumulative distribution functions for humidity, temperature and wind speed

Figure 5.4 consists of cumulative distribution functions for each month for the values of humidity, wind speed and temperature. Humidity is lowest and temperature the highest in the summer months. Wind speed shows less of a seasonal trend, and with less correlation with the time of year. This may be due in part to an averaging effect between the three weather station locations. Also, additional seasonal variations in the wind quantity, such as direction, have not been considered.

Independence of wind speed, temperature and humidity

Given that weather variables are sampled from independent distributions in the Monte Carlo simulations, it is important to investigate the degree of dependence which exists between them. Figure 5.5a and Figure 5.5b show the correlations between wind speed and humidity for the actual daily data and for the simulated data, which is sampled from independent distributions. Figure 5.6 and Figure 5.7 show similar, for humidity and temperature, and wind speed and temperature, respectively.
Figure 5.5 (a & b): Correlation between wind speed and humidity, for daily and simulated weather variables

Figure 5.6 (a & b): Correlation between humidity and temperature, for daily and simulated weather variables

Figure 5.7 (a & b): Correlation between wind speed and temperature, for daily and simulated weather variables
Wind speed shows little correlation to either temperature or humidity, with correlation coefficients less than 0.06 all cases. In the case of the actual daily data, there is a strong negative correlation between humidity and temperature, with a correlation coefficient of -0.77. That is, high temperatures tend to result in low humidity. A similar, but weaker, correlation is seen in the simulated data, with a correlation coefficient of -0.22.

5.1.3 Fire Danger Index distributions

Distributions of Fire Danger Index, from both the Department of CALM’s dataset, and which have been simulated in the Monte Carlo Analysis used in this study, are presented in Figure 5.8, below.

![Figure 5.8: Probability distribution functions and cumulative distribution functions of Fire Danger Index for CALM and simulated data](image)

These distributions appear similar, particularly within the regime below an FDI of 500. The peaks of the distributions are of similar magnitude and occur at the same range of Fire Danger
Index. However, in the Dept. of CALM dataset, there are a greater number of large FDI values than are seen in the simulated distribution. The mean, standard deviation and skewness of these distributions are shown in Table 5.1, below.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dept. of CALM data</td>
<td>187</td>
<td>317</td>
<td>3.7</td>
</tr>
<tr>
<td>Simulated data</td>
<td>100</td>
<td>143</td>
<td>6.9</td>
</tr>
</tbody>
</table>

The greater values of mean and standard deviation in the Dept. of CALM distribution can be attributed to a relatively small number of large values. This suggests that some occasional, extreme values of the Fire Danger Index are not being taken into account in the simulation.

5.1.4 Extreme value distributions

Figure 5.9a shows the return period distribution of the Fire Danger Index, which is the rate of fire spread for standard fuel conditions, and relates to extreme weather events. The return period distribution for the surface moisture content consists of those values of SMC associated with the FDI distribution, such that the two parameters can be used in calculating the Fuel Quantity Correction Factor and intensity. As such it is not strictly a return period distribution. Each of the points represents the result from one of the 50 simulations. The line is the mean value, which is used for this analysis. The range of the other points is a result of the random nature of the simulation, and these give an indication of the error range of the results. In the case of FDI this...
variation increases with increasing return period, such that at the 100 year return period, there is a substantial variation between simulations.

These represent the extreme weather characteristics for the entire forest, and have not yet been scaled.

### 5.1.5 Scaling analysis

The results of the process of running the Monte Carlo simulation for decreasing proportions of yearly events is shown in Figure 5.10. The final FDI return period distribution is reduced accordingly, as is expected given the lower number of events. Similar distributions exist for surface moisture content, but are not presented.

![Figure 5.10: FDI return period distribution, for various proportions of total events](image)

Figure 5.10a shows the result of taking the ratio, $R(p)$, of each of the distributions in Figure 5.10 compared to the distribution in which all fire events have been included in the modelling ($FDI_1(T)$). Figure 5.11b shows the ratios of each of the SMC distributions, compared to that in which all fire events are modelled.
Figure 5.11 (a & b): Ratios of distributions compared to the distribution where all fire events have been modelled.

Figure 5.11a shows a consistent decrease in the ratios of each distribution, with respect to the proportion of events which are modelled. The ratio is also not constant with return period. There is a generally steady decrease in the ratio with return period, which is especially pronounced for higher values.

Figure 5.11b is less ordered. This is because the SMC return period distributions are not ranked distributions, but are simply the values of SMC which correspond to the ranked values of FDI. However, when the ratios are averaged over return period, there is still a general increasing trend as the number of modelled events decreased. This can be observed in Figure 5.12b. Also, there is an increase in the SMC ratio in the low return periods.
Figure 5.12 (a & b): Relationships between the proportion of events modelled and the magnitude of the return period distribution for Fire Danger Index and Surface Moisture Content

Figure 5.12 show the relationship between the averaged values of the ratio of the return period distributions ($R(p)$), and the proportion of events used to model each of these distributions ($p$). The fact that the ratio varies with return period has been ignored in this analysis, for the purpose of finding a simple relationship between the magnitude of the return period distribution and the proportion of fire events. Each of these relationships has been linearly extrapolated to the case of zero events. In the case of FDI, the boundary condition of a ratio of zero for a proportion of zero has been applied, as discussed in Section 4.7.1. In the case of SMC, the relationship has simply been extrapolated until intercepting the y-axis.

The functions presented in Figure 5.12 give the relationship between the proportion of the total number of events in the forest which can be expected in an area, and the magnitude of the FDI return period distribution which can be expected in that area. In this way, an appropriate return period distribution of Fire Danger Index can be created for any section of the forest, if the expected proportion of total events is known.

Both distributions are non-linear, with the variation in magnitude becoming greater as the proportion of events moves closer to 0.

5.1.6 Probability of ignitions

The position of ignition of 4555 fire events, taken from the Department of CALM record, are shown in Figure 5.13a.
Figure 5.13 (a & b): Probability distribution function for the position of fire events in south-west W.A.

Fire events are scattered throughout the south-west, but large numbers of fires occur to the east and north of the Perth metropolitan area, as well as the areas surrounding Dwellingup and Collie. These regions are specified by arrows in Figure 5.13a. The high incidence of fire in these areas is likely due to the nearby populations, resulting in arson and accidental ignitions. Figure 5.13b is the probability distribution function of an event occurring in any of the 10km by 10km grid areas shown in the diagram. There is one grid cell, to the north-east of the Perth metropolitan area, which exhibits an exceptionally high number of ignitions. This has the effect of swamping the visible variation in the remainder of the forest. The majority of grid cells have probabilities of ignitions of less than 0.01.
5.1.7 Fuel load

Figure 5.14a shows the fuel age in years for the forest. Figure 5.14b shows the application of this data to the grid used in this analysis. The fuel age (years) has been converted to fuel load (tonnes/ha) by Equation 4.1, and the average fuel load in each grid cell has been calculated. The fuel load varies across the catchment from 1.0 to 18.54 tonnes/ha. The Dept. of CALM aims to keep fuel load below 6-8 tonnes/ha through its policy of prescribed burning (Peet 1965), however there are still large areas of the forest which exhibit fuel loads substantially greater than this.

In the case of most of the 10 by 10 km grid areas, not all of the squares will lie within the boundaries of the forest. In these cases, the average value of those areas which do have a fuel load assigned to them in the Dept. of CALM data is assigned to the entire grid area. This does not interfere with the remainder of the analysis, with the understanding that a fire in any grid area can only occur in the sub-area which contains a fuel load.

5.1.8 Intensity risk maps

Maps of expected intensity (kW/m) over the catchment, for return periods of 5, 15 and 50 years are given in Figure 5.15. The maps themselves appear identical because the factors defining the
variation between grid squares, probability of ignition and fuel load, remain constant. However, the scale changes significantly. The maximum expected intensities in any one area are approximately 1400, 2100 and 3300 kW/m for the 5, 15 and 50 year events, respectively.

Figure 5.15 (a, b & c): Design intensities (kW/m) for return periods of 5, 15 and 50 years

The variation within each map is defined by the varying fuel load and probability of ignition, which defines the magnitude of the scaled Fire Danger Index distributions. The variation between maps is due to the difference in return period, which determines the value of FDI in each area.
Areas with particularly high expected intensities are those to the north and east of the Perth area, as well as in the vicinity of Collie. These areas appear to coincide with the areas where the probability of an ignition is high (see Figure 5.13).

5.1.9 Controlling variables

![Correlation between intensity and probability of ignition](image1)

![Correlation between intensity and fuel load](image2)

**Figure 5.16 (a & b): Correlations between the expected intensity and probability of ignition, and intensity and fuel load**

The correlations between intensity and probability of ignition, and intensity and fuel load are shown in Figure 5.16. These represent the spatial variables used in the analysis. The correlation coefficient between intensity and ignition probability is 0.78, and between intensity and fuel load 0.21. This shows that the probability of ignition has a much greater influence on the expected intensity that the fuel load in an area. The incidence of large intensities in Figure 5.16b increases markedly when the fuel load is greater than 10 tonnes/ha.

5.1.10 Sensitivity to spatial variables

![Variation of intensity with FDI and Probability](image3)

![Variation of intensity with ignition probability and fuel load](image4)
Figure 5.17 shows the variation of intensity with respect to changes in FDI, the probability of an ignition occurring in a smaller area, and fuel load respectively. In each case, the two other variables are held constant. Due to the covariance of the three variables, the graphs show the sensitivity of intensity with respect to changes in the variable of interest, but are not able to show the relative influence of the three variables.

Intensity varies linearly with FDI, which is expected by the application of the Forest Fire Behaviour Tables, where the intensity is a linear multiple of rate of spread (FDI) and fuel load (see Equation 4.8 and Equation 4.10). Intensity varies with respect to the probability of an event occurring in the location of interest by the same relationship developed in the scaling analysis and shown in Figure 5.12a. In the case of increasing fuel load, there is very little corresponding increase in intensity until the fuel load reaches a value of approximately 5 tonnes/ha.

5.2 Fire Area Modelling

Figure 5.18a shows the intensity along the elliptical fireline, as defined in Equation 4.14, which is being driven in the x direction by the wind speed, u. The intensity is defined by the rate of outward spread of the fireline at all points, as this determines how much fuel is burnt by the moving fire. This is a consequence of Equation 4.10. The greatest intensity can be seen at the front of the fire, since the fire is primarily being driven in this direction by the wind.
Figure 5.18 (a & b): The intensity of the fireline, and the position of the fireline relative to an asset. The asset is shown as an asterisk.

Figure 5.18b shows the position of the fire over time. A point of interest has been defined and is designated by an asterisk. The power at the point over time due to the passing fire is shown in Figure 5.19. The point experiences some power over the life of the fire, but peaks at approximately 5 ½ hours, which corresponds to the fireline passing over the point in Figure 5.18b.

Figure 5.19: The power experienced at a point due to a passing elliptical fire.
6 Discussion

The first part of this chapter (Section 6.1) considers the implications of the results of the study in terms of fire management. Section 6.2 assesses the validity of the methods presented in this study. It includes discussion of the assumptions which have been made in the analysis, and the limitations of the method. This assessment is an important part of this study, as its aim is to investigate methods for estimating wildfire risk, and so a complete understanding of the limitations of the technique is required. Section 6.3 discusses the potential to completely characterise risk, including the role of the results of this study. Sections 6.4 and 6.5 concern the use of risk analysis to develop appropriate management strategies, and the way in which return period analysis may assist this process. Finally, the potential for the use of more complicated fire spread models in a return period analysis is considered in Section 6.6. This section concerns the future direction of return period analysis techniques as applied to wildfire risk quantification.

6.1 Management implications of the results

Figure 5.15 shows the high risk areas to the North and East of Perth and surrounding the town of Collie. The correlations presented in Figure 5.16, as well as the visual similarities between the PDF of ignitions and the intensity risk maps (Figure 5.13 & Figure 5.15) suggest that these areas of high risk (that is, high expected intensity) are being controlled by the chance of ignition, rather than the fuel load. Additionally, this probability of ignition and subsequent expected intensities appear to be controlled by anthropogenic forces. This can be seen in the proximity of high risk areas to populated areas, as well as Department of CALM data (unpublished, See Section 3.1.2) indicating that 71% of fires are started from anthropogenic sources. This may include deliberate ignitions, accidents and escapes from burn offs. 45% of all fires on record are started deliberately.

The significance of ignition to wildfire risk is not taken into account in the hazard reduction policies of prescribed burning, and it may be the case that a policy of education to reduce deliberate and accidental ignitions will be more effective than one of fuel reduction, even if it is more difficult to implement.

Figure 5.16b suggests that very high intensity fires are unlikely to occur in areas with a fuel load less than 10 tonnes/ha, while the results from Figure 5.17c suggest that fuel reduction burning would be most effective when the fuel load is kept below approximately 5 tonnes/ha. These values are in keeping with the Department of CALM’s target of a fuel load below 6-8 tonnes/ha.
(Peet 1965). While the corresponding time since last burn will vary depending on canopy and vegetation structure, if the assumed canopy cover of 50% is taken, then these values correspond to a burning rotation of between 3.5 and 8 years. It is unlikely that such a frequent rotation is ideal for species maintenance, with studies showing that such frequent burning regimes can lead to ecosystem simplification (see Section 2.4.1). This is an example of the conflicting objectives which exist in wildfire risk management. In this case an ideal strategy for reducing the intensity of events which may damage property or human life is in opposition to the objective of species maintenance. The application of alternative mitigation strategies may enable these objectives to be realised concurrently.

An understanding of the danger from wildfire in an area may be obtained by comparing the expected intensity of a fire to the ability to suppress it. The suppression potential of a fire has been defined as Behaviour Classes in the Wildfire Threat Analysis, as given in Table 2.1. Taking the grid square of greatest risk as an example, and comparing its expected intensities to the WTA Behaviour Classes, the 15 year fire event is will not be able to be suppressed by ground forces, and all firefighting efforts are ineffective for the 50 year event. This is vital information in terms of the management of assets in the area. It can be understood that the probability of a fire occurring in each year which cannot be suppressed by a direct ground attack is 1/15, or 6.7%, and decisions as to the management or degree of mitigation required for an asset may be made with this understanding. The application of design standards with this information is discussed in Section 6.5.

### 6.2 Validity of the return period analysis

#### 6.2.1 Weather variables

The correlation seen in the simulated humidity and temperature data, Figure 5.6b, is unexpected given that the values are taken from independent distributions, which should not be correlated. However, this effect is due to the selection of monthly distribution functions. There will be some correlation between these values because of the predictable relationship between humidity and temperature with the month of sampling. The lower, but significant, correlation coefficient of 0.22 for the simulated humidity and temperature reflects the similar relationships of the distribution functions with the season, if not the physical daily processes which relate humidity and temperature. In this way, the interdependence between these variables has been partially captured in this analysis.
The 2-parameter Gamma distribution appears to accurately represent the range of each of the weather variables. This is indicated in the similar ranges between the observed and simulated variables, as seen in Figure 5.5, Figure 5.6 and Figure 5.7.

Weather is considered as a forest-wide average in this analysis. The analysis could be improved by varying the distributions within each area according to the nearest meteorological stations, thus capturing the local meteorological conditions. This would require the recalculation of return period distributions and subsequent scaling analysis for each area in the grid.

6.2.2 Fuel load

Being defined by previous fire events, fuel load shows a high level of spatial variability in keeping with the variation expected in the area burnt by fires. This is due to the variation in both the number of fires which pass through an area, and the within-fire spatial variability. Individual fires show substantial spatial variability in their burn patterns, due to heterogeneity of vegetation, topography, surface moisture content and wind speed (Clark et al. 2002; Catchpole 2002). The process of averaging this variability within each grid area means that estimates of intensity are an average expected intensity for each area, rather than a maximum. The maximum expected intensity could be calculated by taking the largest value of fuel load instead of the average.

The forest fuel load distribution is not constant with time, but varies with annual leaf fall and fire events. However, this time dependence does not interfere with the return period analysis. The intensity return period distributions which have been developed are valid for the current fuel load. If the fuel load changes, either by the annual leaf fall or by fire, the fuel load distribution must be recalculated, to give a new set of return period distributions.

Additionally, there may be some relationship between fuel load and an ignition actually occurring, which has not been captured in this analysis. However, this is likely to be the case only in an immediately post-fire environment, where the fuel load is very near zero. In this case there may be insufficient fuel for an ignition to occur. In practice, this relationship would have little impact on the results of this analysis, since for an area with zero fuel load, the expected intensity of a fire will be zero, in accordance with Equation 4.10.
6.2.3 *FDI distribution*

While the application of weather variable PDFs to simulate the FDI distribution provides a good fit for the bulk of the distribution, it is concerning that the simulated distribution shows fewer events in the larger values than the CALM data distribution. This may be attributed to two possibilities. Firstly, since weather variables (temperature, humidity and wind speed) are sampled independently, there may be a lower probability of potentially dangerous combinations leading to extreme weather conditions. Indeed, Figure 5.6 shows that the correlation between temperature and humidity is only being partially captured. As an example, the well-known heat wave conditions, characterised by unusually high temperatures and a strong inland wind (Underwood & Christensen 1981) suggest a correlation between high wind and high temperature which is not incorporated in the independent selection of wind and temperature. As such, this dangerous combination is not likely to occur in the simulation.

The second possibility is that such conditions only exist in particular geographic locations, for example where topographical conditions intensify wind (Catchpole 2002). The implication of this is that the simulated model may be underestimating the intensities of some extreme events. This is despite the expectation that the weather distributions would provide a ‘maximum’ daily FDI due to their being 3 pm values. The difference in the extreme values of the Fire Danger Index distributions is important in the analysis because these events define the extreme value distribution. Further study is required to capture the factors influencing the differences between the distributions. In particular, joint probability functions should be determined to capture the interdependencies between weather variables.

6.2.4 *Ignition probability*

Using information about the historical ignition regime provides a strong basis for the estimate of the probabilities of the location of future events. However, this method does have limitations.

Firstly, the probability of an ignition in an area is assumed to be the equivalent of the probability of a fire in that area. This makes an assumption regarding the extent of a fire event, by which a fire exists entirely within and encompasses an area. While it is true that a fire which starts in some area will exist in that area, it is also able, and likely in the case of an extreme fire, to be transported to other areas. This means that the use of a probability distribution function of ignitions, rather than of the presence of the fire, is a partial but incomplete estimate of an event occurring within an area of interest.
The issue of capturing the extent of each fire is difficult to address in an area scaling analysis such as this. This problem can be addressed, however, in the use of fire spread models, such as discussed in Section 6.6.

There are additional dependencies which exist between weather conditions and ignition probability, which are not considered in this study. For example, incidents of lightning strike depend on weather. The associated weather conditions may determine whether or not an ignition is successful, for example by affecting surface moisture content. Alternatively, arsonists are known to operate preferentially on high fire danger days, when there is greater impact from their actions (C. Muller, personal communication 2004). These kinds of dependencies are difficult to quantify.

Past ignitions may not completely characterise the ignition regime. The most obvious example of this is in an area of forest which does not have past events on record. The area would be assigned a probability of zero, where there is actually likely to be some small chance of a fire starting.

To address these issues, other options for determining a probability distribution function may be available. A PDF of fire events may be created through an understanding of the processes which create ignitions, rather than by incidents of past ignitions. For example, it is observed that fires occur in areas surrounding townships and highways, as well as within bands where summer storms are likely (Muller 1993, C. Muller personal communication 2004). It is conceivable that a probability distribution function could be estimated based on this underlying understanding, as well as observed data. While including a more complete understanding of the cause of fires, such a method would depend on complex statistics or qualitative estimates, and so may not be as robust as a purely quantitative estimation based on past data. The Wildfire Threat Analysis uses a similar understanding, but captures the probability qualitatively. At this stage there are no documented accounts of such a process being carried out to derive a quantitative estimate.

6.2.5 Scaling analysis

The scaling analysis provides an effective way of determining extreme distributions for specific, smaller areas of interest, without the necessity of small scale modelling or fine-resolution data. The method may equally be applied to any scale – a specific area or a different grid from the
10km x 10km grid which has been applied in this study – as long as the probability of a fire event being in the smaller area can be determined. However, the analysis has two restrictions.

The first is that it relies on the extrapolation which is made below a proportion of events of 0.03. The second is that the scale of interest is limited to the smallest scale for which the probability of a fire occurring, compared to the entire forest, may be determined. As the scale of interest becomes smaller, for example if focussing on a single building or unit of infrastructure, the issue of the extent of fires, as discussed in Section 6.2.4, becomes more important. This is because in a sufficiently small area, the number of ignitions in the area no longer applies, but instead the number of fires which are transported to the point of interest must be used as an estimate of the number of events experienced by the asset. This is another problem addressed in the use of fire spread models (see Section 6.6).

The dependence of the scaling ratio, \( R(p) \), with intensity or return period has been ignored in this study. This variation has the potential to alter the scaled FDI and SMC return period distributions. This ratio could be expressed in terms of a function with a dependence on return period, in order to capture this variation.

### 6.2.6 Limitations of the model

#### Extent & Suppression

There are two important factors which are not captured in this model. Firstly, the spatial transport processes and subsequent extent of fires are not considered in the return period analysis. As discussed in Section 6.2.5, this issue becomes more important when the effect of the fire regime on specific assets is examined. These fire transport processes are not able to be considered in a scaling analysis such as has been employed in this study. Incorporation of these processes requires the use of fire spread modelling, which will be discussed in Section 6.6.

Secondly, suppression activity will affect the burnt area of a fire, and to a lesser degree its intensity. In populated areas such as the South-West forest, suppression activity is likely to define the size of a fire. In particular, strategic decisions will influence the fire. On days with a higher Fire Danger Index there is a greater level of preparedness, which reduces response time and allows for greater suppression activity (Chris Muller 2004 personal communication). Alternatively, on lower FDI days, fires may be allowed to burn throughout areas which are intended to be burnt as part of the fuel reduction policy (Chris Muller 2004 personal...
communication). As such, the extent of a fire is often defined by the suppression decisions. This does not interrupt the analysis if it is considered to concern itself with ‘natural’ events (being without human influence), and suppression is considered as part of an appropriate mitigation strategy to reduce the danger of these events. However, it is preferable to incorporate the effects of suppression activity into the risk analysis, such that its effects can be investigated.

**Portability**

The Forest Fire Behaviour Tables were developed from empirical data taken from fires in Western Australian forest. As a result, this model may not be accurate outside of Western Australia. However, the return period analysis and scaling techniques themselves are portable, given that a fireline intensity prediction model is chosen which is appropriate for the region being studied.

**Other assumptions**

Topography has been assumed to be flat in this study. The Forest Fire Behaviour Tables account for changes in rate of spread with slope by an appropriate multiplication of the fuel corrected rate of spread. However, on a landscape scale the effects of topography average out and are therefore not a concern (Catchpole 2002).

Stationarity has been assumed in the case of all probability distributions. This means that the statistical properties of the distribution do not change with time. This may be challenged in future work. For example, the effects of inter-decadal climate variability, predictable changes in vegetation or changes in the ignition regime may alter these probability distributions. The changes in the distributions of variables due to within-year seasonality will not affect the analysis. This is because the seasonality of the variables has been captured in the model by using separate probability distribution functions for each month of the year.

The distributions of weather variables have been taken from a single year’s record. This may not capture the true mean and range of values, and more accurate distributions could be obtained by the addition of more data.

It must also be understood that all the data employed in this analysis comes from an altered fire regime. This means that the conditions, including fuel load and ignitions, have been altered by and are defined by anthropogenic influences, which change with time and with fire management
policy. In particular, the policy of prescribed burning largely defines the fuel load in the forest (Underwood et al. 1985). Thus, data from which this study is derived is convoluted with historical management practices. This complicates the problem of selecting appropriate mitigation strategies from the results of this and any similar study.

In a return period analysis, there is considerable uncertainty in the estimation of a population of events from a short sample record (Pilgrim 1997). A longer dataset would improve this estimation, particularly in terms of developing a better approximation to the number of events occurring each year.

### 6.3 Completing the assessment of risk

The risk which has been determined in this study relates to primary and secondary risk as defined in the Environmental Risk Management scheme (discussed in Section 2.4.6), and as such provides a valuable but incomplete assessment of the risk to an asset. These categories are the independent probabilities that an event occurs of some specified intensity, and that this event will influence an asset of interest. In this study, a fire is assumed to influence an asset of interest if it occurs in its vicinity.

Estimates of tertiary and quaternary risk are outside the scope of the methods presented in this study. These relate to the probability of a fire causing damage to an asset, given that it reaches the asset, and the probability that the asset can recover from damage (see Section 2.4.6). Although the expected intensity of a fire in an area is an important and useful component of risk, a complete estimation of risk requires estimation of these tertiary and quaternary probabilities.

Since intensity is an indication of damage potential (Catchpole 2002), the expected intensities calculated in this study will influence the tertiary risk. However, the risk will vary greatly with the management of an asset of interest and of the area immediately surrounding it. For example, data from a catastrophic wildfire in south-eastern Australia indicated that 90 percent of houses survived the passage of the wildfire if an able bodied person was in attendance. This same study concluded that the lowering of fuel load in the near vicinity of the house had a major impact on the probability of a house surviving the fire (Wilson & Ferguson 1984). Quaternary risk depends entirely on the asset which is being considered, but is most applicable when considering species or biodiversity as the objectives. In this case, the ability for the natural system to recover from a wildfire will define the risk.
Developing estimates of these tertiary and quaternary risks is more difficult than determining the likelihood and expected intensities of fires in an area. The Wildfire Threat Analysis attempts this determination by overlaying a map of assets over the other factors which influence risk, each with an associated area within which a fire may cause damage (Muller 1993). This is not a quantitative estimate of risk, but nonetheless has value in terms of asset management. The unique circumstances of each asset complicate the estimate of tertiary risk from a fire in its vicinity. Difficulties arise due to the influence of the type and distribution of surrounding vegetation, the fire resistant properties of the asset and the availability of suppression equipment and forces. It may be such that a qualitative assessment can provide a relatively easy and inexpensive, if incomplete, estimate of risk. In this case, the quantitative probability of a fire occurring of some intensity, and the qualitative estimate of the effects of such a fire on the asset may be combined to provide a semi-quantitative estimate of risk. While not as powerful as a quantitative estimate, this is still very valuable from the perspective of risk management. While quantitative estimates of tertiary and quaternary risk should be possible, the difficulties in estimating their values mean that a semi-quantitative risk assessment may be required to include these categories with relative ease.

6.3.1 Suppression

The effects of suppression efforts on fire behaviour are important to risk analysis and may be determined qualitatively or quantitatively, given sufficient knowledge of available fire-fighting assets. The Wildfire Threat Analysis utilises estimates of the time until detection of a fire, the time taken for suppression forces to reach the fire, and the time for an effective strategy to be employed (Muller 1993). These are categorised qualitatively in classes from poor to immediate. However, given sufficient knowledge it may be possible to determine the expected effectiveness of suppression efforts on fireline spread, with appropriate error bounds. Some work has been done in this field, for example by Corlett & Williams (1979). Such a quantitative determination may be possible but difficult, given that the effectiveness of suppression will depend on complex interactions between fire behaviour, the forces available and the fire size when they arrive (Muller 1993).

6.4 Developing appropriate mitigation strategies

The nature of wildfires means that a wide range of mitigation measures are available to a fire management authority. These may include reducing human ignitions, fuel reduction, altering the
nature of structures within risk areas and increasing suppression capabilities. Equally, a wide range of objectives must be considered when deciding on an appropriate combination of mitigation activities, and these may range between protecting biodiversity and property to protecting human life.

The adoption of an objective-centric risk management scheme allows a focus on a range of mitigation options and on the complete range of objectives which must be protected, which may not be possible when effort is concentrated on determining the most appropriate application of hazard reduction. As an example of the recognised necessity of a broad analysis of objectives, the Environmental Protection Authority (2004) has declared that risks to human health from smoke from prescribed burning must be balanced with the increased probability of intense wildfires, and that greater emphasis on biodiversity maintenance should exist in the planning of prescribed burning. This suggests a greater awareness is needed within the management authority as to its full suite of objectives. The EPA continues to say that the objectives of each burn must be clearly specified, and that the level of achievement must be measured (Environmental Protection Authority 2004). This process of measuring success may be derived from the results of this study, where the impact of mitigation actions can be seen to influence risk.

Another difficulty facing fire management is the often conflicting multiple objectives that exist and must be managed in an area (Lindenmayer 2003). As such, all objectives may not be able to be met in an area, and a process of prioritization or optimisation must be applied. For example, in an area where protection of property is a priority, some species may be lost in a frequent prescribed burning regime (Lindenmayer 2003). Supported by knowledge of how mitigation decisions will affect the risk to each objective, the authority may be able to make a better judgement as to the effectiveness or detriment of each policy on the objectives under consideration. For example, given the information in the risk maps in Figure 5.15, a frequent burning regime may be chosen in those areas where the risk to people and property is high, whereas the low-risk squares may be managed primarily for biodiversity. This could focus the prescribed burning regime to allow better management of the broader suite of objectives.

To illustrate the effective selection of mitigation options, an example of the use of asset protection measures occurred in the Eastern Otway Ranges, approximately 100 km south-west of Melbourne. The Ash Wednesday wildfire in February 1983 was of a high intensity and burnt
40,000 ha of the Ranges. High intensity fires had burnt the region in 1980 and 1981 – just 2 and 3 years earlier - but the resulting fuel reduction did not have a substantial effect on the 1983 fires. Private land to the north of this area was last burnt in 1978 - 5 years earlier – but did not burn in the 1983 fire due to protection efforts. The area was surrounded by a road and a large slashed firebreak, and fire-fighting equipment was privately owned and operated. In this case, these measures were more effective but did not require a high frequency burning regime to protect against even this very intense wildfire (Wilson 1996).

6.5 Applications of return period analysis

This study has been developed from the context of engineering design and management. The quantitative estimate of risk, sitting within a structured risk framework – being the Australian/New Zealand Standard for Risk Management and the Environmental Risk Management scheme – has been developed in order to assist the management of the objectives of fire management, these being the protection of assets such as infrastructure, agriculture, property, human life and biodiversity.

An accurate quantification of risk can assist the management authority in a number of ways. The first benefit is properly identifying the main contributors of risk (Spouge 1999). It has been seen in asset protection that hazard, when considered as fuel load, is not always the most appropriate contributor of risk to be mitigated against, and an appropriate understanding of the underlying factors of risk can allow appropriate strategy to be decided (see Section 6.4). For example, the results of this study show that the risk of ignition outweighs the importance of fuel load. Further, risk estimation allows various management options to be compared numerically (Spouge 1999), in order to determine the least-cost or most effective combination of strategies. This is particularly useful when comparing the effects of strategies on conflicting objectives.

Estimates of risk also allow decisions to be made as to whether action needs to be taken to reduce the risks (Spouge 1999; Kohr 1996). The potential exists to develop and apply agreed risk standards. These can provide a consistent and auditable standard as to the level of risk which is acceptable for any objective, and therefore indicate the level of mitigation activity required. Such standards can provide structured and accountable criteria from which mitigation decisions can be made. As well as ensuring appropriate management, comparison to standards can demonstrate acceptability of conditions to regulators or the community (Spouge 1999; Kohr 1996). The acceptable level of risk must vary by objective, for example between the acceptable
risk of the loss of life and that of the loss of property. As an example of such standards, an acceptable risk of individual fatality has been set by the Environmental Protection Authority. In industrial facilities the acceptable level of risk is $5 \times 10^{-5}$ yr$^{-1}$ and for residential zones $1 \times 10^{-6}$ yr$^{-1}$ (Environmental Protection Authority 1992).

There is particular benefit in the independent assessment of the categories of risk, as set out in the Environmental Risk Management Scheme (Goff & Steedman 1997). This is because the effect of mitigation strategies may be examined by observing their impact on the independent category of risk which they affect. For example, reducing ignitions or fuel load will influence the primary risk. The use of better building materials or the better management of areas directly surrounding as asset will affect the tertiary risk. This allows a relatively straightforward assessment of how overall risk will change under various mitigation treatments.

### 6.6 Applications of fire spread modelling

The results presented in Section 5.2 show a crude application of fire spread modelling, to show its capacity to capture the transport processes of fires. In this case, a fire exists and is transported in the vicinity of an asset of interest, and the maximum power output experienced by the asset may be determined.

There is potential to use fire models in a return period analysis. Such methods would involve simulating a series of fires over a landscape, in order to determine the maximum power from each at any point of interest. This has the advantage over the use of a spatial scaling argument, such as is presented in this study, in that it uses a better understanding of fire behaviour and allows a point of interest to be examined, rather than a region.

By examining a regime of many fire events over time, an intensity/return period distribution for any point may be determined. Two possible methods are available, these being hindcasting or forecasting of events. Hindcasting involves knowledge of previous fires which have occurred in an area. The intensities of these events in space and time are then determined by the application of a fire spread model. This method has been applied to the study of cyclones off the North-West of Western Australia (Steedman 1987). It is a robust method in that it is based on the historical fire regime, however this may be very difficult to implement given the scarcity of detailed fire data in Western Australia. Alternatively, fires may be forecast. In this case, a spatial probability distribution of ignitions (similar to that used in this study) may be used to randomly
ignite fires across the landscape over time. The fire spread model may then be used to determine their effect over the landscape.

More complicated fire models than the elliptical case presented in this study exist, as discussed in Section 2.3.3. Similarly, there have been attempts at modelling the fire regime in an area (e.g. McCarthy & Cary 2002), however a return period analysis has not been applied to these results. These more complex numerical models require fine-scale spatial data, and their accuracy will depend on the quality of the data inputs and the appropriateness of the model to Western Australian conditions.

The advantages of using fire spread modelling to estimate a return period distribution are:

1. Capturing the transport processes of fire events allows their shape and extent to be incorporated into the analysis.

2. A better estimate of the effect of the fire regime on an asset may be made, by examining the fires which are transported to a point, rather than simply exist in an area.

3. A sufficiently complex fire spread model can allow the spatial heterogeneity of the landscape to be taken into account, including the local characteristics surrounding an asset. In this way, the effect of mitigation treatments to the immediate area around an asset may be examined. This heterogeneity may include variation in the fuel load, wind fields and topography. As an example, the effects of clearing the area immediately surrounding an asset is known to substantially reduce risk (see Sections 6.3 & 6.4), and such treatments may be incorporated into the analysis.

4. There may be potential to take suppression activities into account to estimate the expected intensity and transport of the firefront. This potential stems from examining a real firefront, where the effects of suppression activity may be incorporated into its behaviour.

5. Improving the complete estimate of risk. Capturing the transport processes completes the estimate of secondary risk, by determining fires which a transported to and affect an asset. Tertiary risk may be partially included, by including the effects of the local characteristics surrounding an asset.
In these ways, the application of fire spread modelling would improve the accuracy and scope of the estimate of risk, and allow a greater range of mitigation options to be considered in the risk analysis model.
7 Conclusions

This study represents a step forward in the estimation of wildfire risk. It has been shown that spatial information can be included in the return period analysis of fire intensity, such that spatial variation in risk may be captured. This variation is due to differences in fuel load and the probability of a fire igniting. As such, there is potential for the application of quantified risk assessment to asset management in fire-prone areas.

Wildfire management currently focuses on hazard reduction in the form of prescribed burning. It has been shown that for fuel reduction burning to be most effective, a frequent rotation of approximately 3.5-8 years is required. However, such a policy may conflict with the objective of species maintenance. Risk has been shown to be controlled more by the probability of a fire igniting near an asset than by the fuel load in the area. As such, while the policy of prescribed burning has doubtless improved the risk of damage to infrastructure and lives, it may not be the most effective risk mitigation strategy.

The policy of prescribed burning would be better implemented under the risk assessment standard AS/NZS 4260:2004, whereby risk is considered from the perspective of the potential for damage of an asset. As such, it would sit within a broader understanding of risk, whereby a full suite of mitigation options may be considered to reduce the risk. These may include hazard reduction by prescribed burning, the use of fire retardant materials in building design, policies to reduce ignition and localised clearing around an asset.

Adopting quantified risk estimates within a risk management framework has the potential to improve the application of management and mitigation strategies. This benefit comes from (1) an improved understanding of the causes of risk, (2) by providing a process by which to measure the impacts of risk mitigation strategies, and (3) by allowing agreed standards to be applied in mitigation decisions. This process allows the most appropriate combination of mitigation activities to be determined. This process may be enhanced if the elements of risk can be defined independently, in keeping with the principles of the Environmental Risk Management Scheme.

Despite the advantages in developing a complete quantitative risk estimate – that is, including primary, secondary, tertiary and quaternary risk – there is still benefit in a semi-quantitative analysis. In cases where the assessment of risk may be difficult, error prone or expensive, a
qualitative or relative assessment may be required. This may be likely in estimates of tertiary or quaternary risk. Such an assessment will not derive all the benefits of a quantitative assessment, but is nonetheless valuable for decision-making.
8 Recommendations

It is recommended that the management authority apply the Australian / New Zealand Standard for Risk Management (AS/NZS 4360:2004) to fire management. Additionally, quantified risk assessment should be pursued for the support of risk management decisions. These measures provide a more robust decision support framework than the hazard management approach which is employed presently.

Agreed design and management standards should be developed for the application of quantified risk estimates. That is, acceptable levels of risk must be determined, depending on the nature of the asset in question. Similar standards exist in other forms of engineering design, and provide effective guidelines for design.

There is potential to improve the estimates of risk which were presented in this study. This may be undertaken in several regards. Firstly, fire spread modelling should be applied in the return period analysis. This enables spatial heterogeneity in the landscape to be captured at all scales. It will allow the transport processes in fire behaviour to be captured, and the analysis will be better able to focus on specific assets. Also, the relationships between weather variables contributing to the Fire Danger Index must be better understood. Specifically, further statistical analysis is required to determine the joint probability distributions of temperature and wind speed.

It is recommended that more work be done toward a complete assessment of risk. Capturing the spatial transport processes of fires is an important aspect of this, and completes the estimate of secondary risk. More work is required to quantify the potential for damage and recovery of an asset, given that it is affected by a fire. This would include a greater quantitative understanding of the effects of fires on structures, and of the effects of suppression activities.
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Appendix A: Derivation of the elliptical fire spread model

This appendix gives the derivation of the fire spread equations used in this study.

By the method presented in Catchpole et al (1982), a fire ignited from a point source will grow as an ellipse under the influence of constant wind, such as shown in Figure A1:

![Figure A1: Quantities involved in the elliptical fire model. Modified from Catchpole et al. (1982)](image)

In Figure A1, \( R_0 \) is the rate of spread of the fire under zero wind conditions, and the coefficients \( f, g \) and \( h \) define the shape of the firefront. The coefficient \( g \) relates to the distance between the centre of the ellipse and the ignition point. The fire has a shape factor of \( f/h \), which is the ratio between the major and minor radii of the ellipse. This shape factor can be derived from the wind speed\(^1\), \( u \).

Any point, \((x,y)\), on the ellipse is given by:

\[
\begin{align*}
    x &= R_0 t (g + f \cos(\theta)) \\
    y &= R_0 th \sin(\theta)
\end{align*}
\]

Equation A1

By differentiating with respect to \( t \), the velocity components in the directions \( x \) and \( y \) are for any point on the fire front are:

\[
\begin{align*}
    v_x &= R_0 (g + f \cos(\theta)) \\
    v_y &= R_0 h \sin(\theta)
\end{align*}
\]

The velocity of the fire front in the direction of the normal is therefore:

\[ R = \frac{(R_h g \cos(\theta) + f)}{\sqrt{h^2 \cos^2(\theta) + f^2 \sin^2(\theta)}} \]

Using the equation \( I = H \nu r \), the intensity at any point on the fireline can be calculated:

\[ I = \frac{H \nu (R_h g \cos(\theta) + f)}{\sqrt{h^2 \cos^2(\theta) + f^2 \sin^2(\theta)}} \text{, measured in kW/m.} \]

The power output from any point on the fireline is then equal to \( I \delta s \), where \( s \) is the arc length. So:

\[ P(\theta) = I(\theta) \delta \theta = \frac{H \nu (R_h g \cos(\theta) + f)}{\sqrt{h^2 \cos^2(\theta) + f^2 \sin^2(\theta)}} \delta s \]

Consider a point of interest, designated by \( O = (x_0, y_0) \) in the diagram below.

For any point \( A = (x(\theta, t), y(\theta, t)) \), the distance between \( A \) and \( O \) is \( d \), where:

\[ d = \sqrt{(x_0 - x(\theta, t))^2 + (y_0 - y(\theta, t))^2} \]

The heat output at any point, \( A \), on the fireline, will drop off by the inverse of the distance squared, such that the energy absorbed by the point \( O (P_0) \) from the radiation from point \( A (P_0) \) is:

---

2 Byram (1959) equation, taken from Catchpole (2002). This is discussed in Section 4.4.1.
\[ P_0 = \frac{P_1^3}{d^2} \]
\[ P_0(\theta) = \frac{I_d(\theta)\delta\theta}{d^2} = \frac{Hw R_0 h (g \cos(\theta) + f)}{d^2 \sqrt{h^2 \cos^2(\theta) + f^2 \sin^2(\theta)}} \delta s \]

So, the total power absorbed at O is given by the sum of the power absorbed from each point on the fireline, thus:

\[ P_{0,\text{Total}} = \int_0^{2\pi} \frac{I_d(\theta)\delta\theta}{d^2} \quad \text{where} \quad d = d(\theta) \]
\[ P_{0,\text{Total}} = \int_0^{2\pi} \frac{Hw R_0 h (g \cos(\theta) + f)}{d^2 \sqrt{h^2 \cos^2(\theta) + f^2 \sin^2(\theta)}} \delta s \]
\[ P_{0,\text{Total}} = Hw R_0 h \int_0^{2\pi} \frac{(g \cos(\theta) + f)}{\left[ (x_0 - x(\theta,t))^2 + (y_0 - y(\theta,t))^2 \right] \sqrt{h^2 \cos^2(\theta) + f^2 \sin^2(\theta)}} \delta s \quad \text{Eqn A2} \]

The arc length (\( \delta s \)) of an ellipse may be written as:

\[ \delta s = f \left[ 1 - \left(1 - \frac{h^2}{f^2}\right) \sin^2(\theta) \right]^{1/2} \delta \theta \]

Equation A3

Where \( f \) and \( h \) have been defined in Figure A1 and correspond to the major and minor radii. Substituting Equations A3 and A1 into A2, we have:

\[ P_{0,\text{Total}} = 0.47w R_0 h \int_0^{2\pi} \frac{(g \cos(\theta) + f) f \left[ 1 - \left(1 - \frac{h^2}{f^2}\right) \sin^2(\theta) \right]^{1/2}}{\left[ (x_0 - R_0 f (g + f \cos(\theta))^2 + (y_0 - R_0 h \sin(\theta))^2 \right] \sqrt{h^2 \cos^2(\theta) + f^2 \sin^2(\theta)}} \delta \theta \]

where in the case of Australian fuels, \( Hw = 0.47w \), where \( w \) is expressed in tonnes/ha, and \( w \) in m/hr. This equation can be integrated numerically, and represents the power absorbed at the point O, due to a fireline defined by \( g, h, f \) and \( t \). These parameters depend on the wind speed and the expected rate of spread in zero-wind conditions⁴.

⁴ For an discussion of how shape factors are defined by the wind speed, see: Finney, M.A. 1998, FARSITE: Fire Area Simulator – Model Development and Evaluation, Research Paper RMRS-RP-4, US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT.
Appendix B: MatLab scripts used in the analysis

**Calmanalysis.m**

% CALManalysis is the master file for the return period analysis. It takes in the data required for the % analysis, and runs a Monte Carlo analysis for decreasing proportions of the total number of events. It then outputs % figures, and writes appropriate data to the disk for the use of 'locations.m'

clear all;
close all;
no_simulations = input('enter number of simulations 
');
yrs = input('enter desired length (in years) of simulated record 
');

CC=50;
%The line below allows the user to enter the canopy cover if it is activated:
% CC = input('enter canopy cover (0-100%) to determine fuel load (default value- enter 50) ');

%READ IN DATA------------------------------------------------------------------------------
[fire_date, cause, FDI, sum_area] = textread('date-cause-FDI-area.txt', '%s %d %d %f', 'delimiter', '	');
[month_num1, temp1, humidity1, wspeed1] = textread('dwellingyup_3pm_month_temp_humidity_wind.txt', '%d %f %f %d', 'delimiter', '	');
[month_num2, temp2, humidity2, wspeed2] = textread('jarrahwood_3pm_month_temp_humidity_wind.txt', '%d %f %f %d', 'delimiter', '	');
[month_num3, temp3, humidity3, wspeed3] = textread('pearceraaf_3pm_month_temp_humidity_wind.txt', '%d %f %f %d', 'delimiter', '	');

month_num = [month_num1; month_num2; month_num2];    %concatenate weather variables to create net vectors from all sites.
temp = [temp1; temp2; temp3];
humidity = [humidity1; humidity2; humidity3];
wspeed = [wspeed1; wspeed2; wspeed3];
clear month_num1 month_num2 month_num3;       %clear temporary variables
clear temp1 temp2 temp3;
clear humidity1 humidity2 humidity3;
clear wspeed1 wspeed2 wspeed3;

figure
loglog(humidity,wspeed * log((1-2/3)/0.13) / log((10-2/3*1.5)/0.13*1.5),'.')
xlabel('Humidity (%)')
ylabel('Fuel Height Wind (kmh^-1)')
tmp = corrcoef(humidity,wspeed * log((1-2/3)/0.13) / log((10-2/3*1.5)/0.13*1.5));
title(['Daily dataset: Correlation coefficient: ', num2str(tmp(1,2))])
axis([1 100 0.1 100])

figure
loglog(temp, humidity, '.')
xlabel('Temperature (°C)')
ylabel('Humidity (%)')
tmp = corrcoef(temp, humidity);
title(['Daily dataset: Correlation coefficient: ', num2str(tmp(1,2))])

figure
loglog(temp,wspeed * log((1-2/3)/0.13) / log((10-2/3*1.5)/0.13*1.5),'.')
xlabel('Temperature (\textdegree\text{C})')
ylabel('Fuel Height Wind (\text{km}\textsuperscript{-1})')
tmp = corrcoef(temp,wspeed * log((1-2/3)/0.13) / log((10-2/3*1.5)/0.13*1.5));
title(['Daily dataset: Correlation coefficient: ', num2str(tmp(1,2))])
axis([1 100 0.1 100])

%CREATE PDFs WITH GRAPHICS---------------------------------------------------------------
%note that the function 'pdf.m' requires the use of the 'dateconverter.m' m-file.
[p_greaterthan10, cum_FDIprob, FDI_bins, cdf_humidity, humidity_class, cdf_temperature, temperature_class, cdf_month, cdf_wspeed, wspeed_class]= pdf(fire_date, cause, FDI, sum_area, CC, month_num, temp, humidity, wspeed);

%event_proportion_vector defines the proportion of total events which is modelled
event_proportion_vector = [1 0.8 0.6 0.4 0.2 0.1 0.05 0.03]; % = [1] %should be made equal to 1 if correlations.m or sensitivity.m are to be run

for prop_num = 1:length(event_proportion_vector)
    event_proportion = event_proportion_vector(prop_num);
    %MONTE CARLO SIMULATION------------------------------------------------------------------
    for k=1:no_simulations
        %input desired number of years of simulation
        %use the function 'monte_carlo.m' to do the simulation
        [sim_num, sim_FDI, sim_SMC, sim_humidity, sim_temperature, sim_wspeed]=
        monte_carlo(event_proportion, yrs,p_greaterthan10, cum_FDIprob, FDI_bins, cdf_humidity, humidity_class, cdf_temperature, temperature_class, cdf_month, cdf_wspeed, wspeed_class);

        %ANNUAL MAXIMUM SERIES----------------------------------------------------------------
        ------
        % select largest FDI fire from each year (column) in the matrix
        [ams_FDI(k,:), index] = max(sim_FDI);
        %create FDI_corres_SMC
        for i = 1:length(index)
            SMC_corres(i) = sim_SMC(index(i),i); %SMC_corres is the set of smc data which corresponds to the FDI values (aes_FDI)
            humidity_corres(i) = sim_humidity(index(i),i);
            temperature_corres(i) = sim_temperature(index(i),i);
            wind_corres(i) = sim_wspeed(index(i),i);
        end
        %FDI_corres_SMC is the combination of the two to be sorted together wrt FDI
        FDI_corres_SMC_humidity_temperature_wind = [ams_FDI(k,:); SMC_corres; humidity_corres; temperature_corres; wind_corres];

        sorted_FDI_corres_SMC_etc = -1.*sort(-1.*(FDI_corres_SMC_humidity_temperature_wind),1);
        sorted_ams_FDI(k,:) = sorted_FDI_corres_SMC_etc(1,:);
        sorted_ams_SMC(k,:) = sorted_FDI_corres_SMC_etc(2,:);
        sorted_ams_humidity(k,:) = sorted_FDI_corres_SMC_etc(3,:);
        sorted_ams_temperature(k,:) = sorted_FDI_corres_SMC_etc(4,:);
        sorted_ams_wspeed(k,:) = sorted_FDI_corres_SMC_etc(5,:);

        %assign a rank m to each element (largest -> m=1)
        %obtain return period using T= (N+1)/m where N is length of record
        for i=1:length(sorted_ams_FDI(k,:))
            ret_period(i)= (length(sorted_ams_FDI(k,:))+1)/i;
        end
    end
end
% Ranking fires by FDI
% take the top fire from each distribution:
% need to convert from an array to a column matrix
for i=1:yrs
    for j=1:max(sim_num)
        column_sim_mat(i,1)= max(sim_FDI(:,i));
        a=find(sim_FDI(:,i)==max(sim_FDI(:,i)));
        column_sim_mat(i,2)=sim_SMC(a(1),i);
        column_sim_mat(i,3)=sim_humidity(a(1),i);
        column_sim_mat(i,4)=sim_temperature(a(1),i);
        column_sim_mat(i,5)=sim_wind(a(1),i);
    end
end

% sort the fires by FDI
ams_sorted_sim_FDI= -sortrows(-(column_sim_mat), 1);
% place the simulated data into an array
ams_fire_array{k}= ams_sorted_sim_FDI;
end % end 'k' loop
%
% delete extraneous "dummy" variables:
clear ams_sorted_sim_inten aes_sorted_by_inten
clear column_sim_mat
clear col_sim_FDI col_sim_SMC col_sim_fuel col_sim_inten col_FQCF a
clear sorted_sim_inten sorted_FQCF sorted_sim_FDI sorted_sim_SMC sorted_sim_fuel
clear ams_sorted_sim_inten aes_sorted_sim_inten
clear aesfire_matrix
clear ams_FDI ams_SMC ams_fuel

% ANNUAL MAXIMA SERIES---------------------------------------------------------------
% obtain relevant information from the array
for i=1:no_simulations
    ams_FDI_matrix(:,i)= ams_fire_array{i}(:,1);
    ams_SMC_matrix(:,i)=ams_fire_array{i}(:,2);
    ams_humidity_matrix(:,i) = ams_fire_array{i}(:,3);
    ams_temperature_matrix(:,i) = ams_fire_array{i}(:,4);
    ams_wind_matrix(:,i) = ams_fire_array{i}(:,5);
end
% obtain mean from each simulation
ams_mean_FDI_matrix = mean(ams_FDI_matrix');
% ams_mean_fuel_matrix=mean(ams_fuel_matrix');
ams_mean_SMC_matrix=mean(ams_SMC_matrix');
% ams_mean_inten_matrix=mean(ams_inten_matrix');
ams_mean_humidity_matrix = mean(ams_humidity_matrix');
ams_mean_temperature_matrix = mean(ams_temperature_matrix');
ams_mean_wind_matrix = mean(ams_wind_matrix');

clear ams_fire_array;
% save the output of the mean intensity matrix to a file for the use of the spatial model:
if event_proportion == 1  % only do this for the case of all fires being modelled
    save ret_period_FDI_SMC.mat ret_period ams_mean_FDI_matrix ams_mean_SMC_matrix
    save calmanalysis_individual_variables.mat ret_period ams_FDI_matrix ams_SMC_matrix ams_humidity_matrix
    ams_temperature_matrix ams_wind_matrix
end

% create pdf of modelled FDI's
count = 1;
for i = 1:size(sim_FDI,1)  % take care of sim_FDI being a matrix, and get rid of zero values
    for j = 1:size(sim_FDI,2)
        if (sim_FDI(i,j) ~= 0)
            sim1d_FDI(count) = sim_FDI(i,j);
            sim1d_SMC(count) = sim_SMC(i,j);
            count = count + 1;
        end
    end
end

% set bin width h
h=20;
% create bins
FDI_bins = 0:h:max(sim1d_FDI)+h;
[FDIfreq, FDIclass]=hist(sim1d_FDI,FDI_bins);
FDIprob=FDIfreq./sum(FDIfreq);
fprintf('The average of the simulated FDI is %g, the standard deviation is %g and the skewness is %g\n',
    mean(sim1d_FDI), std(sim1d_FDI), skewness(sim1d_FDI))

% plot the histogram
figure
bar(FDI_bins, FDIprob,1);
title('Probability Distribution Function for Fire Danger Index (FDI) - Simulated')
xlabel('Fire Danger Index')
ylabel('Probability')
axis([0 3000 0 .3])

% calculate the CDF (only used for display, not in the simulation):
FDI_counter=0;
for i=1:length(FDIfreq);
    cum_FDIprobsim(i)=FDIfreq(i)+FDI_counter;
    FDI_counter= cum_FDIprobsim(i);
end
% plot the cumulative histogram
figure
plot(FDI_bins, cum_FDIprobsim);
title('Cumulative Probability Distribution Function for Fire Danger Index (FDI) - Simulated')
xlabel('Fire Danger Index')
ylabel('Probability')
axis([0 3000 0 1])

% plot the histogram for surface moisture content values:
% set bin width h
h=1;
% create bins
SMC_bins = 0:h:max(sim1d_SMC)+h;
[SMCfreq, SMCclass]=hist(sim1d_SMC,SMC_bins);
SMCprob=SMCfreq./sum(SMCfreq);
% plot the histogram
figure
    bar(SMC_bins, SMCprob,1);
    title('Probability Distribution Function for Surface Moisture Content (SMC) - Simulated')
    xlabel('Surface Moisture Content')
    ylabel('Probability')
    axis([-h/2,max(SMC_bins),0,max(SMCprob)+0.1]);

% plot the results of each ams simulation:
figure
    semilogx(ret_period, ams_FDI_matrix, '.', ret_period, ams_mean_FDI_matrix, '-*', 'LineWidth', 2)
    ylabel('FDI')
    xlabel('Return period (yrs)')
    title('Return period vs Fire Danger Index (FDI)')

figure
    semilogx(ret_period, ams_SMC_matrix, '.', ret_period, ams_mean_SMC_matrix, '-*', 'LineWidth', 2)
    ylabel('SMC')
    xlabel('Return period (yrs)')
    title('Return period vs Surface Moisture Content (SMC)')

% Look at simulated correlations between weather variables:
    counter = 1;
    for i = 1:size(sim_FDI,1)
        for j = 1:size(sim_FDI,2)
            if sim_FDI(i,j) ~= 0        % only use those events where intensity is not zero.
                vec_temperature(counter) = sim_temperature(i,j);
                vec_SMC(counter) = sim_SMC(i,j);
                vec_humidity(counter) = sim_humidity(i,j);
                vec_FDI(counter) = sim_FDI(i,j);
                vec_wind(counter) = sim_wind(i,j);
                counter = counter + 1;
            end
        end
    end

figure
    loglog(vec_humidity,vec_wind,'.')
    xlabel('Humidity (%)')
    ylabel('Wind (kmh^-1)')
    tmp = corrcoef(vec_humidity, vec_wind);
    title(['Simulated dataset, independently selected variables: Correlation coefficient: ',
                num2str(tmp(1,2))])
    axis([1 100 0.1 100])

figure
    loglog(vec_temperature, vec_humidity,'.')
    xlabel('Temperature (°C)')
    ylabel('Humidity (%)')
    tmp = corrcoef(vec_temperature, vec_humidity);
    title(['Simulated dataset, independently selected variables: Correlation coefficient: ',
                num2str(tmp(1,2))])
    axis([1 100 1 100])

figure
    loglog(vec_temperature,vec_wind,'.')
xlabel('Temperature (°C)')
ylabel('Wind (km^-1)')
tmp = corrcoef(vec_temperature, vec_wind);
title(['Simulated dataset, independently selected variables: Correlation coefficient: ',
num2str(tmp(1,2))])
axis([1 100 0.1 100])
end

fprintf('
Calculated for proportion %g', event_proportion);
prop_mean_FDI_matrix(prop_num,:) = ams_mean_FDI_matrix;
prop_mean_SMC_matrix(prop_num,:) = ams_mean_SMC_matrix;
end

save prop_mean_FDI_matrix.mat prop_mean_FDI_matrix
save prop_mean_SMC_matrix.mat prop_mean_SMC_matrix
save event_proportion_vector.mat event_proportion_vector

%plot the results of the various proportion simulations
figure
semilogx(ret_period, prop_mean_FDI_matrix', '.', 'LineWidth', 2)
ylabel('FDI')
xlabel('Return period (yrs)')
title('Return period vs FDI (mean) for various relative number of events')
legend('Proportion = 1','Proportion = 0.8','Proportion = 0.6','Proportion = 0.4','Proportion = 0.2','Proportion = 0.1','Proportion = 0.05','Proportion = 0.03')

correlations.m

%'correlations.m' determines the correlations between fuel, burnt area and FDI and creates
%plots of the correlations. Run this after the CALMAnalysis model, after changing the event_proportion_vector = [1].
%It will correlate with the last simulation. These are correlations using all fires, not just the extreme events.

%create vectors from matrices - all sim_*'s are the same dimensions:
d = size(sim_FDI);
count = 1;
for i = 1:d(1)
for j = 1:d(2)
vec_temperature(count) = sim_temperature(i,j);
vec_SMC(count) = sim_SMC(i,j);
vec_humidity(count) = sim_humidity(i,j);
vec_FDI(count) = sim_FDI(i,j);
vec_wind(count) = sim_wind(i,j);
if sim_FDI(i,j) ~= 0
    count = count + 1;
end
end
end

figure
loglog(vec_humidity,vec_wind,'.')
xlabel('Humidity (%)')
ylabel('Wind (kmh^-1)')
tmp = corrcoef(vec_humidity, vec_wind);
title(["Simulated dataset, independently selected variables: Correlation coefficient: ", num2str(tmp(1,2))])

figure
loglog(vec_temperature, vec_humidity,'.')
xlabel('Temperature (°C)')
ylabel('Humidity (%)')
tmp = corrcoef(vec_temperature, vec_humidity);
title(["Simulated dataset, independently selected variables: Correlation coefficient: ", num2str(tmp(1,2))])

figure
loglog(vec_temperature,vec_wind,'.')
xlabel('Temperature (°C)')
ylabel('Wind (km^-^1)')
tmp = corrcoef(vec_temperature, vec_humidity);
title(["Simulated dataset, independently selected variables: Correlation coefficient: ", num2str(tmp(1,2))])

dateconverter.m

function [day, month,year]= dateconverter(datestring)
% dateconverter.m converts strings of dates from the form dd/mm/yy to date, month, and year numeric values. It is used by pdf.m

if length(char(datestring)) == 9
    datestring1= char(datestring);
    ch_day= datestring1(1);
    ch_month= strcat(datestring1(3),datestring1(4));
    ch_year= strcat(datestring1(6), datestring1(7), datestring1(8), datestring1(9));
elseif length(char(datestring)) == 10
    datestring1 = char(datestring);
    ch_day= strcat(datestring1(1), datestring1(2));
    ch_month= strcat(datestring1(4),datestring1(5));
    ch_year= strcat(datestring1(7), datestring1(8), datestring1(9), datestring1(10));
end
char(ch_day);

day= [str2num(ch_day), str2num(ch_month), str2num(ch_year)];

locations.m

% locations.m is the main file which incorporates the spatial data into the return period distribution. The distribution is scaled down in accordance with ignition probability and fuel load. This file outputs graphs of ignitions, fuel load and the spatial fire risk maps.

clear all;
close all
[east_loc, north_loc] = textread('location-east-north.txt', '%d %d', 'delimiter', 't');
%load coastline data:
load WAcoast3.txt

east = WAcoast3(:,1);
north = WAcoast3(:,2);

% the following code reads in the necessary data for the forest areas:
% ----------------------------------
load forest_1km_rastert2.txt

x = 1:1:size(forest_1km_rastert2,2);
y = 1:1:size(forest_1km_rastert2,1);

y = -sort(-y);

for i = 1:max(y)        % this sorts out the fact that there are many values in the matrix.
    for j = 1:max(x)
        if forest_1km_rastert2(i,j) ~= 0
            forest_1km_rastert2(i,j) = 1;
        end
    end
end

% the following code adjusts the x and y values such that they fit into the appropriate coordinates.
% the coordinates at the top left corner are: (taken from original file):
% xllcorner     306841.21621536
% yllcorner     6117944.4658673
x = (x + 306) * 1000;
y = (y + 6117) * 1000;      % the 4th (or 5th) digit is the one-kilometre scale. the * 100 is to compensate for the fact that
these are 1km cells not 1m.
% ----------------------------------
figure
plot(east_loc,north_loc,'x','MarkerSize',3)
axis([3*10^5 5.5*10^5 6.1*10^6 6.6*10^6])
title(['ontsize{13}Location of ', num2str(length(east_loc)), ' fire events'])
set(gca,'DataAspectRatio',[1 1 1], 'PlotBoxAspectRatio',[1 1 1])
set(gcf, 'color', [1 1 1])
% Superimpose coastline on diagram.
hold on
plot(east,north,'.k','MarkerSize',3);
set(gcf, 'color', [1 1 1])
hold off

% initialise grid which is 0.1x10^5 units in resolution and within the range given by the axis command (3-5.5x10^5 by
6.1-6.6x10^6)
resolution = 1*10^4;        % resolution can change but needs to be able to divide 500000 and 250000 into a whole
number. Can also try 0.5, 1, 2.5. Resolution is in metres
fire_count = zeros(500000/resolution,250000/resolution);
% go through the location data and put in the appropriate bins
for i = 1:length(east_loc)
    [tmp_row, tmp_col] = loc2element(north_loc(i), east_loc(i), resolution);
    fire_count(tmp_row, tmp_col) = fire_count(tmp_row, tmp_col) + 1;
end

% normalise fire_count so that it gives probabilities:
fire_prob = fire_count / sum(sum(fire_count));
view_fire_prob = fire_prob;  %create view_fire_prob, used for visualisation
for i = 1:size(view_fire_prob,1)
    for j = 1:size(view_fire_prob,2)
        if view_fire_prob(i,j) == 0
            view_fire_prob(i,j) = -max(max(view_fire_prob))*0.05;
        end
    end
end

%graph the PDF of fire events:
x = 3*10^5:resolution:5.499*10^5;
y = -sort(-y);  %take care of the y-axis being the wrong way round.
figure
h = pcolor(x,y,view_fire_prob);
set(gca,'DataAspectRatio',[1 1 1],'PlotBoxAspectRatio',[1 1 1])
colormap(gray)
brighten(0.4)
cmp = colormap;
cmp(1,:) = [.5 .6 .5];
colormap(cmp);
colorbar
set(gcf, 'color', [1 1 1])
set(h, 'EdgeAlpha', 0)
title('PDF of fire events in Northern Jarrah Forest')
hold on
plot(east,north,'.','MarkerSize',3);
set(gcf, 'color', [1 1 1])
hold off

load ret_period_FDI_SMC.mat  %This obtains ret_period.

%Get the fuel loads corresponding to each gridsquare of resolution 'resolution'.
fuel_load_tensor = zeros(size(view_fire_prob));
load rastert_yssl1a.txt  %this is the years since last burnt data from CALM
%convert from years since burn to fuel load: Use eqn for available litter from Beck p334, Karri forest prediction eqn
%fjarrah, available fuel factor AFF =1, assume canopy cover =50%
AFF = 1;
CC = 50;  %canopy cover
for i = 1:size(rastert_yssl1a,1)
    for j = 1:size(rastert_yssl1a,2)
        if rastert_yssl1a(i,j) ~= -9999
            NJ_L_wt = (0.18.*CC+11.06).*(1-exp(-0.086.*rastert_yssl1a(i,j)));
            rastert_yssl1a(i,j) = NJ_L_wt.*AFF;
        end
    end
end

%ancilliary data for rastert_yssl1a.txt:
% ncols     299
% nrows     455
% xllcorner 307541.54286719
% yllcorner 6116627.1750574
% cellsize  1000
% NODATA_value -9999
% NOTE THAT THERE ARE NO 0 TERMS IN RASTERT-YSLB1.TXT

depth_count = zeros(size(view_fire_prob));
% create a grid of coordinates:
for i = 1:size(rastert_yslb1a,1)
    for j = 1:size(rastert_yslb1a,2)
        raster_coordx = 307541 + j*1000;
        raster_coordy = 6116627+1000*455 - i*1000;
        if ((raster_coordy <= 6.6*10^6) & (raster_coordy > 6.1*10^6) & (raster_coordx < 5.5*10^5) & (raster_coordx > 3*10^5))
            if (rastert_yslb1a(i,j) ~= -9999)
                [tmp_row, tmp_col] = loc2element(raster_coordy, raster_coordx, resolution);
                fuel_load_tensor(tmp_row,tmp_col,depth_count(tmp_row,tmp_col)+1) = rastert_yslb1a(i,j);
                depth_count(tmp_row,tmp_col) = depth_count(tmp_row,tmp_col) + 1;
            end
        end
    end
end
% now average each depth in the fuel_load_tensor to get fuel_load;
% initialise fuel_load
fuel_load = zeros(size(view_fire_prob));
for i = 1:size(fuel_load_tensor,1)
    for j = 1:size(fuel_load_tensor,2)
        total = 0;
        for k = 1:depth_count(i,j)
            total = total + fuel_load_tensor(i,j,k);
        end
        if depth_count(i,j) ~= 0
            fuel_load(i,j) = total / depth_count(i,j);
        else
            fuel_load(i,j) = 1;         % This fills in the blank fuel loads for areas outside the specified forest.
        end
    end
end

figure
h=pcolor(x,y,fuel_load);
colorbar
set(gca,'DataAspectRatio',[1 1 1],'PlotBoxAspectRatio',[1 1 1])
colormap(gray)
cmp = colormap;
colormap([-cmp]);
set(gcf, 'color', 
title('Fuel load (tonnes/ha)')
hold on
plot(east,north,'.','MarkerSize',3);
set(gcf, 'color', 
hold off

% Designate a design intensity:
design_probability = 1./input('Enter design return period (yrs): ');
%now, must construct an intensity vs return period curve for each gridsquare, using the known fuel load and the graph of FDI/SMC vs return period. Best if this is done, and the probabilities are created within one loop, to avoid using arrays. This loop determines one_dim_prob for each gridsquare, then this is multiplied by view_fire_prob to get %view_design_prob_matrix below.

load prop_mean_FDI_matrix;
load event_proportion_vector;
load prop_mean_SMC_matrix;
for i = 1:size(prop_mean_FDI_matrix,1)
    ratios_FDI(i,:) = prop_mean_FDI_matrix(i,:) ./ prop_mean_FDI_matrix(1,:);
    ratios_SMC(i,:) = prop_mean_SMC_matrix(i,:) ./ prop_mean_SMC_matrix(1,:);
end

mean_FDI_ratio = mean(ratios_FDI');
mean_SMC_ratio = mean(ratios_SMC');
%include the boundary condition that as proportion --> 0, ratio --> 0.
mean_FDI_ratio(2:length(mean_FDI_ratio)+1) = mean_FDI_ratio;
mean_FDI_ratio(1) = 0;
mean_SMC_ratio(2:length(mean_SMC_ratio)+1) = mean_SMC_ratio;
mean_SMC_ratio(1) = 0;

% include the boundary condition that as proportion --> 0, ratio --> 0.
mean_FDI_ratio(2:length(mean_FDI_ratio)+1) = mean_FDI_ratio;
mean_FDI_ratio(1) = 0;
mean_SMC_ratio(2:length(mean_SMC_ratio)+1) = mean_SMC_ratio;
mean_SMC_ratio(1) = 0;

if ((design_probability < min(1./ret_period)) | (design_probability > max(1./ret_period)))
    fprintf('WARNING: The design probability is outside the domain of the scaled intensity-probability curve'n)
    fprintf('Minimum intensity is %d ; max intensity is %d
',min(scaled_ams_mean_inten_matrix),max(scaled_ams_mean_inten_matrix));
end

for i = 1:size(view_fire_prob,1)
    for j = 1:size(view_fire_prob,2)
        if fuel_load(i,j) > 0       %ensures that are not calculating intensity for those gridsquares where there is no fuel.
            %scaling of SMC and FDI comes in here:
            scaled_ams_mean_SMC_matrix =
            ams_mean_SMC_matrix*interp1(event_proportion_vector(1:length(event_proportion_vector)-1),mean_SMC_ratio,view_fire_prob(i,j),'linear','extrap');  %where the proportion is equal to view_fire_prob(i,j)
            scaled_ams_mean_FDI_matrix =
            ams_mean_FDI_matrix*interp1(event_proportion_vector,mean_FDI_ratio,view_fire_prob(i,j),'linear','extrap');
        end
    end
end

for ret_num = 1:length(ret_period)
    %calc intensity for each fire, by calc FQCF for each fire in the 1d matrix:
    if fuel_load(i,j) <= 8 & scaled_ams_mean_SMC_matrix(ret_num) <=26 &
        scaled_ams_mean_SMC_matrix(ret_num) >=3
        FQCF(ret_num)= 1.02/(1+7266.83*exp(-1.36*fuel_load(i,j)))+0.1;
    elseif (scaled_ams_mean_SMC_matrix(ret_num) <=9) & (fuel_load(i,j) > 8) &
        scaled_ams_mean_SMC_matrix(ret_num)>3
        FQCF(ret_num)= (6.03+5.81*fuel_load(i,j))/53.44;
    elseif (scaled_ams_mean_SMC_matrix(ret_num) > 9) & (scaled_ams_mean_SMC_matrix(ret_num) <= 18) &
        (fuel_load(i,j) > 8)
        FQCF(ret_num)= (11.19+2.92*fuel_load(i,j))/35.02;
    elseif (scaled_ams_mean_SMC_matrix(ret_num) > 18) & (fuel_load(i,j) > 8)
        FQCF(ret_num)= (0.055+0.0023*fuel_load(i,j))/0.074;
    elseif scaled_ams_mean_SMC_matrix(ret_num)==0;
        FQCF(ret_num)=0;
end
ROS(ret_num) = FQCF(ret_num).*scaled_ams_mean_FDI_matrix(ret_num);
end
scaled_ams_mean_inten_matrix = 0.47.*ROS.*fuel_load(i,j);  %this ams_mean_inten_matrix is the vector of intensities corresponding to ret_period
design_intensity_matrix(i,j) = interp1(1./ret_period,scaled_ams_mean_inten_matrix,design_probability);
end
end
end
end
end
end
end
end

contour_intensity = design_intensity_matrix;  %initialises contour_intensity
for i = 1:size(design_intensity_matrix,1)
    for j = 1:size(design_intensity_matrix,2)
        if design_intensity_matrix(i,j) < 0
            design_intensity_matrix(i,j) = -max(max(design_intensity_matrix))*0.05;       %These loops just for purposes of display
            contour_intensity(i,j) = 0;
        end
    end
end
end

dx = 3*10^5:resolution:5.499*10^5;
y = -sort(-y);      %take care of the y-axis being the wrong way round.
figure
h=pcolor(x,y,design_intensity_matrix);
colorbar
set(gca,'DataAspectRatio',[1 1 1],'PlotBoxAspectRatio',[1 1 1])
colormap(copper)
brighten(0.4)
cmp = colormap;
cmp(1,:) = [0.5 .6 .5];
colormap(cmp);
set(gcf, 'color', [1 1 1])
title(['Design intensities for ', num2str(1/design_probability), ' year event'])

%Superimpose coastline on diagram.
hold on
plot(east,north,'.','MarkerSize',3);
set(gcf, 'color', [1 1 1])
hold off

x = 3*10^5:resolution:5.499*10^5;
y = -sort(-y);      %take care of the y-axis being the wrong way round.
figure
h=contour(x,y,contour_intensity,20); %
colorbar
set(gca,'DataAspectRatio',[1 1 1],'PlotBoxAspectRatio',[1 1 1])
colormap(copper)
brighten(0.4)
cmp = colormap;
colormap(cmp);
set(gcf, 'color', [1 1 1])
title(['Design intensities for ', num2str(1/design_probability), ' year event'])

%Superimpose coastline on diagram.
hold on
plot(east,north,'.','MarkerSize',3);
set(gcf, 'color', [1 1 1])
hold off

%Below here is analytical stuff
%Fuel load given by: fuel_load. 1’s everywhere a fuel load is not specified.
%Probability of ignition given by: view_fire_prob - 'no value' is negative.
%intensity given by: design_intensity_matrix - 'no value' is negative.
%all are 50 x 25 matrices.

%going to take the non-zero values from these and put them in a vector, then plot.
count = 1;
for i = 1:size(view_fire_prob,1)
    for j = 1:size(view_fire_prob,2)
        if view_fire_prob(i,j) >= 0
            prob_fuel_inten(count,:) = [view_fire_prob(i,j) fuel_load(i,j) design_intensity_matrix(i,j)];
            count = count + 1;
        end
    end
end

figure
plot(prob_fuel_inten(:,1),prob_fuel_inten(:,3),'.')
xlabel('Areal probability')
ylabel('Intensity')
tmp = corrcoef(prob_fuel_inten(:,1),prob_fuel_inten(:,3));
title(['Correlation = ', num2str(tmp(1,2))])

figure
plot(prob_fuel_inten(:,2),prob_fuel_inten(:,3),'.')
xlabel('Fuel load')
ylabel('Intensity')
tmp = corrcoef(prob_fuel_inten(:,2),prob_fuel_inten(:,3));
title(['Correlation = ', num2str(tmp(1,2))])

monte_carlo.m

function [sim_num, sim_FDI, sim_SMC, sim_humidity, sim_temperature, sim_wind] = monte_carlo(event_proportion, yrs, p_greaterthan10, cum_FDIprob, FDI_bins, cdf_humidity, humidity_class, cdf_temperature, temperature_class, cdf_month, cdf_wspeed, wspeed_class)

%monte_carlo.m completes the monte carlo simulation for any number of years (passed in 'yrs'), and any proportion of %total events (passed in 'event_proportion'). It is called by CALMAnalysis.m

%MONTE CARLO SIMULATION-------------------------------------------------------------------------
%randomly generate number of fire years
N = rand([1, yrs]);

%convert these random numbers (probabilities) to number of fires from the distribution above
p_greaterthan10(length(p_greaterthan10)+1)=0;
for i=1:length(N)
for j=1:length(p_greaterthan10)
    if N(i)>p_greaterthan10(j)
        sim_num(i)=j;    %sim_num gives the number of fires for each simulation year
        break
    end
end

sim_num = round(sim_num * event_proportion);

%randomly generate FDI and fuel values for each fire in each year
sim_FDI= zeros(max(sim_num), length(N));    %initialise a matrix to store FDI values
sim_fuel= zeros(max(sim_num), length(N));   %initialise a matrix to store fuel values
sim_SMC= zeros(max(sim_num), length(N));   %initialise a matrix to store SMC values

for i=1:length(N)
    M = rand([1, sim_num(i)]);  %generate random probability of each fire occurring in a given year
    H = rand([1, sim_num(i)]);  %the three random variables are so FDI, fuel and SMC are independent.
    L = rand([1, sim_num(i)]);  %and humidity and temp are independent
    K = rand([1, sim_num(i)]);
    Q = rand([1, sim_num(i)]);  %for month

    for j=1:length(M)
        %month
        for r = 1:length(cdf_month)    %randomise month
            if Q(j)<cdf_month(r)
                sim_month(j,i)=r;
                break
            end
        end

        %Windspeed (requires sim_month)
        for m = 1:length(cdf_wspeed)
            if M(j)<cdf_wspeed(sim_month(j,i),m)
                sim_wind(j,i)=wspeed_class(m);      %sim_wind
                break
            end
        end

        %humidity
        for o = 1:length(cdf_humidity)
            if H(j)<cdf_humidity(sim_month(j,i),o)
                sim_humidity(j,i)=humidity_class(o);
                break
            end
        end

        %Temperature
        for p = 1:length(cdf_temperature)
            if K(j) < cdf_temperature(sim_month(j,i),p)
                sim_temperature(j,i) = temperature_class(p);
                break
            end
        end

        %Surface (litter) moisture content
        sim_SMC(j,i) = 5.658 + 0.04651.*sim_humidity(j,i) + 3.151*10^-4.*(sim_humidity(j,i).^3)./sim_temperature(j,i) - 0.1854.*sim_temperature(j,i).^0.77;

    end
end

%FDI
%get fdi from SMC and wind here. Taken from FFBT
\[ \text{sim}_\text{FDI}(j,i) = (21.37 - 3.42 \cdot \text{sim}_\text{SMC}(j,i) + 0.085 \cdot (\text{sim}_\text{SMC}(j,i))^2) + (48.09 \cdot \text{sim}_\text{SMC}(j,i) \cdot \exp(-0.6 \cdot \text{sim}_\text{SMC}(j,i)) + 11.90) \cdot \exp(\text{sim}_\text{wind}(j,i) \cdot (-0.0096 \cdot (\text{sim}_\text{SMC}(j,i))^1.05 + 0.44)) \]

if \( \text{sim}_\text{FDI}(j,i) > 3000 \)
    fprintf(\'\text{sim}_\text{wind} = %d, sim_\text{humidity} = %d, sim_\text{temperature} = %d, sim_\text{SMC} = %d, sim_\text{FDI} = %d, sim_\text{wind}(j,i), sim_\text{humidity}(j,i), sim_\text{temperature}(j,i), sim_\text{SMC}(j,i), sim_\text{FDI}(j,i)\); \nend
end %end \text{\textit{j}} \text{\textit{\textit{loop}}} 
end %end \text{\textit{i}} \text{\textit{\textit{loop}}} 

\textbf{pdf.m}

% 'pdf.m' creates and plots the probability distribution functions which are used by 'monte_carlo.m'. These are the % number of fires per year, temperature, humidity and wind speed per month.

function \([p \_\text{greaterthan10}, \text{cum}_\text{FDIprob}, \text{FDI}_\text{bins}, \text{cdf}_\text{humidity}, \text{humidity}_\text{class}, \text{cdf}_\text{temperature}, \text{temperature}_\text{class}, \text{cdf}_\text{month}, \text{cdf}_\text{wspeed}, \text{wspeed}_\text{class}] = \text{pdf}(\text{fire}_\text{date}, \text{cause}, \text{FDI, sum}_\text{area, CC, month}_\text{num, temp, humidity, wspeed})\)

% CAUSE OF FIRE-------------------------------------------------------------
% create histogram of fire causes
% initiate fire cause variables by cause:
deliberate= 0;
calm_escape= 0;
escape_burn_off = 0;
rec_accident= 0;
ti_accident =0;
lightning =0;
other_accident=0;
other=0;
unknown=0;
% count the number of fires that occur due to each cause:
for i=1:length(cause)
    if cause(i) == 1
        deliberate = deliberate+1;
    elseif cause(i) == 2
        calm_escape= calm_escape+1;
    elseif cause(i) == 3
        escape_burn_off= escape_burn_off+1;
    elseif cause(i) == 6
        rec_accident= rec_accident+1;
    elseif cause(i) == 4
        ti_accident= ti_accident+1;
    elseif cause(i) == 5
        other_accident= other_accident+1;
    elseif cause(i) == 7
        lightning = lightning+1;
    elseif cause(i) == 9
        other= other+1;
    elseif cause(i) == 8 | cause(i) == 0
        unknown = unknown+1;
    end
end
cause= [deliberate, calm_escape, escape_burn_off, rec_accident, ti_accident, other_accident, lightning, other, unknown];
for i=1:length(cause)
    prob_cause(i)= cause(i)/sum(cause);
end

figure
bar(prob_cause,1)
colormap hsv
% legend(xcause);
xlabel('Cause')
ylabel('Probability of ignition')
title('Probability mass function of fire ignition by cause')

%-------FIRE DANGER INDEX (weather)--------------------------------------------------------------
%if FDI>3000, then assume an error and force FDI=3000
count_extreme_FDI=0;
for i=1:length(FDI)
    if FDI(i)>3000
        FDI(i)=0;
        count_extreme_FDI= count_extreme_FDI+1;
    end
end

%create a histogram of FDI (aggregate weather factors)
%set bin width h
h=20;
%create bins
FDI_bins = 0:h:max(FDI)+h;

%create a histogram with bins centred on elements of FDI_bins=FDi class, and frequency FDi freq
[FDIfreq, FDIclass]=hist(FDI,FDI_bins);
FDIprob= FDIfreq./sum(FDIfreq);

fprintf('The average of the CALM FDI is %g, the standard deviation is %g and the skewness is %g\n', mean(FDI), std(FDI), skewness(FDI))

%plot the histogram
figure
bar(FDI_bins, FDIprob,1);
title('Probability Distribution Function for Fire Danger Index (FDI) - CALM Data')
xlabel('Fire Danger Index')
ylabel('Probability')
axis([0 3000 0 .3])

% %create cumulative histogram ready to fit a distribution
FDI_counter=0;
for i=1:length(FDIprob);
    cum_FDIprob(i)=FDIprob(i)+FDI_counter;
    FDI_counter= cum_FDIprob(i);
end
% %plot the cumulative histogram
figure
plot(FDI_bins, cum_FDIprob);
title('Cumulative Probability Distribution Function for Fire Danger Index (FDI) - CALM Data')
xlabel('Fire Danger Index')
ylabel('Probability')
axis([-h/2,max(FDI_bins),0,1]);

clear h;
clear FDI;
clear FDI_counter;

% NUMBER OF FIRES
%----------------------------------
% create a histogram of number of fires/year
% firstly convert string cell array into numerical form
for i=1:length(fire_date)
    date_matrix(i,:)= dateconverter(fire_date(i));
end

% determine the number of fires with an area greater than or equal to 10ha in each year
area_10plus= zeros(length(sum_area),1);
for i=1:length(sum_area)
    if sum_area(i)>=10 % this is the place we set the arbitrary 10ha area limit
        area_10plus(i)=date_matrix(i,3);
    end
end
% create a histogram then drop all the zero values (0 = fire had an area less than 10ha)
% define the length of the record for the histogram:
yearspan_1= 1980:1993;
yearspan_2= 2000:2003;
yearspan= [0,yearspan_1,yearspan_2];

[ann_freq1, ann_class1]=hist(area_10plus,yearspan);
% drop the zero values
for i=1:length(ann_freq1)-1
    ann_freq(i)= ann_freq1(i+1);
    ann_class(i)= ann_class1(i+1);
end
clear ann_freq1;
clear ann_class1;

% allocate consecutive numbers to yearspan and plot number of fires in each year
figure
year= 1:length(yearspan)-1;
bar(year, ann_freq);
xlabel('Year number')
ylabel('Number of fires')
title('Number of fires with an area greater than 10ha for each year of record')

% now need to plot the probability that, in a given year, more than 'n' fires occur that are greater than 10ha.
% assume that number of fires is poisson distributed- determine the sample mean number of fires
mu_number= sum(ann_freq)/length(year); % mean number of fire per year

% probabilities are given by (exp(-mean)*mean^year)/year!
% eg prob of 36 fires in a year p_36= (exp(-mu_number)*mu_number^36)/factorial(36)
for i=1:max(ann_freq)
    prob_number(i)= (exp(-mu_number)*mu_number^i)/factorial(i);
end
% now obtain the probability that the number of fires in a year is at least n: = 1 - P(X<n)
% where P(X<n)= sum(p(i))*delta(x(i)). Since delta(x)=1, then this is just sum(p(i))
number_counter = 0;
% create a cumulative histogram to get P(X<n):
for i = 1:length(prob_number)
    p_lessthan10(i) = prob_number(i) + number_counter;
    number_counter = p_lessthan10(i);
end
clear number_counter;
% obtain P(X>n), the probability of obtaining n fires with an area greater than 10ha in a given year
p_greaterthan10 = 1 - p_lessthan10;
figure
plot(p_greaterthan10);  % exceedence probability
xlabel('Number of fires with an area exceeding 10ha');
ylabel('Probability of occurrence in a given year');
clear area_10plus;
clear fire_date;

% TIME TEMPERATURE, HUMIDITY AND WINDSPEED
% Create the cdfs of temperature, humidity and windspeed. SMC is calculated from these in monte_carlo.m
month = date_matrix(:,2);
% create frequency and probability (pdf) distributions of events wrt month.
month_freq = zeros(12,1);
for i = 1:length(month)
    month_freq(month(i)) = month_freq(month(i)) + 1;
end
month_prob = month_freq/sum(month_freq);
% create a cdf of month_prob
cdf_month(1) = month_prob(1);
for i = 2:length(month_prob)  % length(month_prob) is equal to 12
    cdf_month(i) = cdf_month(i-1) + month_prob(i);
end
% plot the pdf of month_prob
figure
bar(1:12,month_prob)
xlabel('Month of ignition')
ylabel('Probability of ignitions')
title('Probability of event occurring in each month of the year')
set(gca,'XTickLabel',{'Jan','Feb','Mar','Apr','May','Jun','Jul','Aug','Sept','Oct','Nov','Dec'})

% create matrix temperature_month, humidity_month and windspeed_month, which has columns of month and rows of
temperature values
temperature_month(month_num(1), 1) = temp(1);  % initialise
humidity_month(month_num(1), 1) = humidity(1);
windspeed_month(month_num(1), 1) = windspeed(1);
for i = 2:length(month_num)
    temperature_month(month_num(i), size(temperature_month,2)+1) = temp(i);
    humidity_month(month_num(i), size(humidity_month,2)+1) = humidity(i);
    windspeed_month(month_num(i), size(windspeed_month,2)+1) = windspeed(i);
end
%now get probability distributions of temperature and humidity and windspeed for each month

for i = 1:12  % this loop gets the mu values for humidity and temperature for each month.
    counta = 1;
    countb = 1;
    countc = 1;
    for j = 1:length(temperature_month(i,:))  % this loop gets rid of the zeros at the end of temperature_month and
        humidity_month for months will less than 31 days
            if temperature_month(i,j) ~= 0          % it assumes that the length of temperature_month is the same as that of
                tmp_temp(counta) = temperature_month(i,j);
                counta = counta + 1;
            end
            if humidity_month(i,j) ~= 0
                tmp_humidity(countb) = humidity_month(i,j);
                countb = countb + 1;
            end
        end
    end
% %for poisson fit
%     mu_temperature_month(i) = poissfit(tmp_temp);
%     mu_humidity_month(i) = poissfit(tmp_humidity);
%     mu_wspeed_fuelheight_month(i) = poissfit(tmp_wspeed * log((1-2/3)/0.13) / log((10-2/3*1.5)/0.13*1.5)); % this
% is where the wind ratio is taken into account. Is eqn 3.2 from Viney phd, with WINGfg = 1.5m and z = 10m (BOM pers.
% comm.)
%     clear tmp_temp tmp_humidity tmp_wspeed;
% end
%
% humidity_class = 0:100;
% temperature_class = 0:45;
% wspeed_class = 0:0.2:11;
% for i = 1:12
%     cdf_humidity(i,:) = poisscdf(humidity_class, mu_humidity_month(i,1), mu_humidity_month(i,2));
% end
% %end piosson fit
%for gamma fit
%     mu_temperature_month(i,:) = gamfit(tmp_temp);
%     mu_humidity_month(i,:) = gamfit(tmp_humidity);
%     mu_wspeed_fuelheight_month(i,:) = gamfit(tmp_wspeed * log((1-2/3)/0.13) / log((10-2/3*1.5)/0.13*1.5)); % this
% is where the wind ratio is taken into account. Is eqn 3.2 from Viney phd, with WINGfg = 1.5m and z = 10m (BOM pers.
% comm.)
%     clear tmp_temp tmp_humidity tmp_wspeed;
% end
cdf_temperature(i,:) = gamcdf(temperature_class, mu_temperature_month(i,1), mu_temperature_month(i,2));
cdf_wspeed(i,:) = gamcdf(wspeed_class, mu_wspeed_fuelheight_month(i,1), mu_wspeed_fuelheight_month(i,2));
%cdf_wspeed is the cdf of the windspeed at the height of the fuel.
end
% end gamma fit
% now make sure that the final value in the CDF is 1. This is because the poisson distribution is open ended, and an error may occur.
cdf_humidity(:,length(cdf_humidity)) = 1;
cdf_temperature(:,length(cdf_temperature)) = 1;
cdf_wspeed(:,length(cdf_wspeed)) = 1;

% and plot SMC pdf:
figure
plot(humidity_class, cdf_humidity)
title('CDF of relative humidity (%)')

figure
plot(temperature_class, cdf_temperature)
title('CDF of temperature (deg C)')

figure
plot(wspeed_class, cdf_wspeed)
title('CDF of wind speed (km/h)')
legend('Jan','Feb','Mar','Apr','May','Jun','Jul','Aug','Sept','Oct','Nov','Dec')

scale_analysis.m

% scale_analysis.m is the file which determines the relationships between the proportion of events in the Monte Carlo analysis, and the magnitude of the FDI return period distribution. This file plots the relationships, but the code is duplicated in CALMAnalysis.m for the actual simulation
% This must be run after CALMAnalysis, such that the appropriate variables have been saved. These are:
% ret_period_FDI_SMC, prop_mean_FDI_matrix, event_proportion_vector, prop_mean_SMC_matrix

clear all;
close all;
load ret_period_FDI_SMC; %for ret_period
load prop_mean_FDI_matrix;
load event_proportion_vector;
load prop_mean_SMC_matrix;

for i = 1:size(prop_mean_FDI_matrix,1)
    ratios_FDI(i,:) = prop_mean_FDI_matrix(i,:) ./ prop_mean_FDI_matrix(1,:);
    ratios_SMC(i,:) = prop_mean_SMC_matrix(i,:) ./ prop_mean_SMC_matrix(1,:);
end

figure
semilogx(ret_period,ratios_FDI')
xlabel('Return Period')
ylabel('Ratio of FDI to distribution with all events')
legend('Proportion = 1','Proportion = 0.8','Proportion = 0.6','Proportion = 0.4','Proportion = 0.2','Proportion = 0.1','Proportion = 0.05','Proportion = 0.03')
title('Ratio of FDI - return period distributions for various proportions')
axis([0 100 0 1.2])

figure
semilogx(ret_period,ratios_SMC')
xlabel('Return Period')
ylabel('Ratio of SMC to distribution with all events')
legend('Proportion = 1','Proportion = 0.8','Proportion = 0.6','Proportion = 0.4','Proportion = 0.2','Proportion = 0.1','Proportion = 0.05','Proportion = 0.03')
title('Ratio of SMC - return period distributions for various proportions')
axis([0 100 0.8 2.2])

mean_FDI_ratio = mean(ratios_FDI');
mean_SMC_ratio = mean(ratios_SMC');

% include the boundary condition that as proportion --> 0, ratio --> 0.
mean_FDI_ratio(length(mean_FDI_ratio)+1) = 0;
event_proportion_vector(length(event_proportion_vector)+1) = 0;

figure
plot(event_proportion_vector, mean_FDI_ratio)
xlabel('Proportion of events')
ylabel('Scaling ratio for FDI')
title('Scaling ratio for FDI, as a function of the proportion of events')

% because of adding in the boundary condition, can do an interpolation within the bounds of 0 and 1. BC does not exist for SMC case

figure
plot(event_proportion_vector(1:length(event_proportion_vector)-1), mean_SMC_ratio)
xlabel('Proportion of events')
ylabel('Scaling ratio for SMC')
title('Scaling ratio for SMC, as a function of the proportion of events')

figure
plot(0:0.1:1, interp1(event_proportion_vector(1:length(event_proportion_vector)-1),mean_SMC_ratio,0:0.1:1,'linear','extrap'))
xlabel('Proportion of events')
ylabel('Extrapolated scaling ratio for SMC')
title('Extrapolated scaling ratio for SMC, as a function of the proportion of events')

figure
plot(0:0.1:1, interp1(event_proportion_vector,mean_FDI_ratio,0:0.1:1,'linear','extrap'))
xlabel('Proportion of events')
ylabel('Extrapolated scaling ratio for FDI')
title('Extrapolated scaling ratio for FDI, as a function of the proportion of events')

loc2element.m

% 'loc2element.m' takes a location in UTM coordinates, and assigns the grid coordinate that this sits in. It is called % from 'locations.m' when data is being fed into the grid.
function [row, column] = loc2element(distancey, distancex, resolution)  %distancey is north, distancex is east

%error checking:
if ((length(distancey) > 1) | (length(distancex) > 1))
    fprintf('This function will not accept vector input')  %this is so the next if statement will work
    return
end
if ((distancey >= 6.6*10^6) | (distancey < 6.1*10^6) | (distancex > 5.5*10^5) | (distancex < 3*10^5))
    fprintf('Input northing and easting are outside the spatial domain\n')
    return;
end

%get row (northing):
row = floor((0.5 - (distancey/10^6 - 6.1)) / resolution * 10 * 100000);
%get column (easting):
column = ceil((distancex/10^5 - 3) * 100000 / resolution);
return

sensitivity.m

% 'sensitivity.m' is a variation on 'locations.m', but which runs through values of fuel load, ignition probability and
% the Fire Danger Index in order to develop maps of the variation in expected intensity with variation in each of these
% variables. Like 'correlations.m', it should be run after running 'CALManalysis.m' changing event_proportion_vector
% = [1].

clear all;
close all

load ret_period_FDI_SMC.mat  %This now obtains ret_period.
%the following are the ranges of each variable which are considered.
fuel_load = 1:18;
view_fire_prob = 0:0.1:1;
design_period = 2:100;

%now, must construct an intensity vs return period curve for each gridsquare, using the known fuel load and the graph of
%FDI/SMC vs return period. Best if this is done, and the probabilities are created within one loop, to avoid using
%arrays. This loop determines one_dim_prob for each gridsquare, then this is multiplied by view_fire_prob to get
%view_design_prob_matrix below.
load prop_mean_FDI_matrix;
load event_proportion_vector;
load prop_mean_SMC_matrix;

for i = 1:size(prop_mean_FDI_matrix,1)
    ratios_FDI(i,:) = prop_mean_FDI_matrix(i,:) ./ prop_mean_FDI_matrix(1,:);
    ratios_SMC(i,:) = prop_mean_SMC_matrix(i,:) ./ prop_mean_SMC_matrix(1,:);
end
mean_FDI_ratio = mean(ratios_FDI);
mean_SMC_ratio = mean(ratios_SMC);
%include the boundary condition that as proportion --> 0, ratio --> 0.
mean_FDI_ratio(2:length(mean_FDI_ratio)+1) = mean_FDI_ratio;
mean_FDI_ratio(1) = 0;
event_proportion_vector(2:length(event_proportion_vector)+1) = event_proportion_vector;
event_proportion_vector(1) = 0;
% mean_FDI_ratio(length(mean_FDI_ratio)+1) = 0;
% event_proportion_vector(length(event_proportion_vector)+1) = 0;
% if ((design_probability < min(1./ret_period)) | (design_probability > max(1./ret_period)))
%   fprintf('WARNING: The design probability is outside the domain of the scaled intensity-probability curve\n')
%   fprintf('Minimum intensity is %d ; max intensity is %d
',min(scaled_ams_mean_inten_matrix),max(scaled_ams_mean_inten_matrix));
%   %break
% end
for i = 1:length(view_fire_prob)
    fprintf('Calculating iteration %g of %g.
',i,length(view_fire_prob))
    for j = 1:length(fuel_load)
        for k = 1:length(design_period)
            if fuel_load(j) > 0 % ensures that are not calculating intensity for those gridsquares where there is no fuel.
                % scaling of SMC and FDI comes in here:
                scaled_ams_mean_SMC_matrix = ams_mean_SMC_matrix*interp1(event_proportion_vector(1:length(event_proportion_vector)-
                1),mean_SMC_ratio,view_fire_prob(i),'linear','extrap'); % where the proportion is equal to view_fire_prob(i,j)
                scaled_ams_mean_FDI_matrix = ams_mean_FDI_ratio*interp1(event_proportion_vector,mean_FDI_ratio,view_fire_prob(i),'linear','extrap');
            end
            for ret_num = 1:length(ret_period)
                % calc intensity for each fire, by calc FQCF for each fire in the 1d matrix:
                if fuel_load(j) <= 8 & scaled_ams_mean_SMC_matrix(ret_num) <=26 &
                    scaled_ams_mean_SMC_matrix(ret_num) >=3
                    FQCF(ret_num)= 1.02/(1+7266.83*exp(-1.36*fuel_load(j)))+0.1;
                elseif (scaled_ams_mean_SMC_matrix(ret_num) <=9) & (fuel_load(j) > 8) &
                    scaled_ams_mean_SMC_matrix(ret_num)>3
                    FQCF(ret_num)= (6.03+5.81*fuel_load(j))/53.44;
                elseif (scaled_ams_mean_SMC_matrix(ret_num) > 9) & (scaled_ams_mean_SMC_matrix(ret_num) <= 18)
                    & (fuel_load(j) > 8)
                    FQCF(ret_num)= (11.19+2.92*fuel_load(j))/35.02;
                elseif (scaled_ams_mean_SMC_matrix(ret_num) > 18) & (fuel_load(j) > 8)
                    FQCF(ret_num)= (0.055+0.0023*fuel_load(j))/0.074;
                elseif scaled_ams_mean_SMC_matrix(ret_num) ==0
                    FQCF(ret_num)=0;
                end
                ROS(ret_num) = FQCF(ret_num).*scaled_ams_mean_FDI_matrix(ret_num);
                end
                scaled_ams_mean_inten_matrix = 0.47.*ROS.*fuel_load(j); % this ams_mean_inten_matrix is the vector of intensities corresponding to ret_period
                design_intensity_matrix(i,j,k) = interp1(1./ret_period,scaled_ams_mean_inten_matrix,1./design_period(k));
            end
        end
    end
end
% so now design_intensity_matrix is the design intensity for any combination of return period (surrogate for FDI), probability and fuel load.
% with design_intensity_matrix(i,j,k) -- i - fire prob; j - fuel load; k - return period (FDI)

% so, first hold fire prob constant and fuel load constant and see variation with return period:
for i = 1:length(design_period)
    unscaledFDI_ret(i) = interp1(1./ret_period,ams_mean_FDI_matrix,1./design_period(i));
end
figure
clear intensity_vector
for i = 1:size(design_intensity_matrix,3)
    intensity_vector(i) = design_intensity_matrix(2,8,i);
end
plot(unscaledFDI_ret,intensity_vector)
title(['Variation of Intensity with FDI - Fuel load = ',num2str(fuel_load(8)),' Probability = ',num2str(view_fire_prob(2)),'
xlabel('FDI')
ylabel('Intensity (kW/m)')

%now, hold fuel load and return period constant and vary ignition probability
figure
clear intensity_vector
for i = 1:size(design_intensity_matrix,1)
    intensity_vector(i) = design_intensity_matrix(i,5,5);
end
plot(view_fire_prob,intensity_vector)
title(['Variation of Intensity with Ignition prob - Fuel load = ',num2str(fuel_load(5)),' Return period = ',num2str(design_period(5))])
xlabel('Probability of ignition')
ylabel('Intensity (kW/m)')

% now, hold return period and ignition probability constant, and vary fuel load.
figure
clear intensity_vector
for i = 1:size(design_intensity_matrix,1)
    intensity_vector(i) = design_intensity_matrix(i,8,50);
end
plot(view_fire_prob,intensity_vector)
title(['Variation of Intensity with Ignition prob - Fuel load = ',num2str(fuel_load(8)),' Return period = ',num2str(design_period(50))])
xlabel('Probability of ignition')
ylabel('Intensity (kW/m)')

% now, hold return period and ignition probability constant, and vary fuel load.
figure
clear intensity_vector
for i = 1:size(design_intensity_matrix,2)
    intensity_vector(i) = design_intensity_matrix(2,i,5);
end
plot(fuel_load,intensity_vector)
title(['Variation of Intensity with Fuel load - Ignition prob = ',num2str(view_fire_prob(2)),' Return period = ',num2str(design_period(5))])
xlabel('Fuel load (tonnes/ha)')
ylabel('Intensity (kW/m)')

figure
clear intensity_vector
for i = 1:size(design_intensity_matrix,2)
    intensity_vector(i) = design_intensity_matrix(10,i,90);
end
plot(fuel_load,intensity_vector)
title(['Variation of Intensity with Fuel load - Ignition prob = ',num2str(view_fire_prob(10)),' Return period = ',num2str(design_period(90))])
xlabel('Fuel load (tonnes/ha)')
ylabel('Intensity (kW/m)')

ellipse.m

% Geometrical / elliptical model
% This file, 'ellipse.m' calculates and shows the output of an elliptical fire moving through space near an asset, and the % subsequent power at that asset over time. Also outputs the intensity of a general firefront using the elliptical model.

clear all;
close all;
global H w f g h h R0 x0 y0 int_t

%Define the fuel load and amount of heat released:
H = 0.47;
w = 6;

%Define the properties of the ellipse:
f = 2; %length of the major radius
g = 1.8; %relates to the distance the centre of the ellipse is downwind from the ignition point.
h = 1; %length of the minor radius
R0 = 10; %burning rate of fuel under zero wind (should probably be lower)

%Define the position of the asset:
x0 = 50; %These coordinates are from the ignition point of the fire.
y0 = 50;

%Show the fire front through time, including the position of the asset.
time = 1:2:10;
for t = 1:length(time)
    theta = 0:0.1:2*pi;
    %clear x y
    for i = 1:length(theta)
        x(i,t) = R0*time(t)*(g + f*cos(theta(i)));
        y(i,t) = R0*time(t)*h*sin(theta(i));
    end
end
plot(x,y)
title('Variation of Intensity with Fuel load - Ignition prob = ',num2str(view_fire_prob(2)),' Return period = ',num2str(design_period(5)))
xlabel('Fuel load (tonnes/ha)')
ylabel('Intensity (kW/m)')
end
end

plot(x,y)
axis equal
legend(["Time = ", num2str(time(1)), ' hr'], ["Time = ", num2str(time(2)), ' hr'], ["Time = ", num2str(time(3)), ' hr'], ["Time = ", num2str(time(4)), ' hr'], ["Time = ", num2str(time(5)), ' hr'])
hold on
plot(x0,y0,'*','MarkerSize', 10)
hold off

%now, show the power absorption at the point at each timestep

clear time;
time = 1:0.1:10;  %define new time intervals for second graph
for t = 1:length(time)
    int_t = time(t);
    power(t) = H*w*R0*h* quad(@ellipsefun, 0, 2*pi);    %Get power by numerical integration.
end

figure
plot(time,power)
xlabel('time (hours)')
ylabel('Power absorbed at asset (kW)')

%What is the intensity around a single fireline?
clear x y;
theta = 0:0.1:2.1*pi;
for i = 1:length(theta)
    x(i) = R0*time(1)*(g + f*cos(theta(i)));
    y(i) = R0*time(1)*h*sin(theta(i));
    intensity(i) = h^w*R0*h*(g*cos(theta(i)) + f) / sqrt(h^2*cos(theta(i))^2 + f^2*sin(theta(i))^2);
end

figure
plot3(x,y,intensity)
grid on
xlabel('x')
ylabel('y')
zlabel('Intensity at each point along the fireline Wm^-1')

%Define the properties of the ellipse, this time by u and rate of spread, R:
u = 5;
R = 5;  %could get from FFBT
LB = 0.936*exp(0.2566*u)-0.461*exp(-0.1548*u)-0.397;
HB = (LB + (LB^2 - 1)^0.5) / (LB - (LB^2 -1)^0.5);
f = (R+R/HB)*.5;  %length of the major axis
g = f-R/HB;    %relates to the distance the centre of the ellipse is downwind from the ignition point.
h = 0.5*(R+R/HB)/LB;  %length of the minor axis
R0 = 10;   %burning rate of fuel under zero wind (should probably be lower)
%note, f and h may actually be half the lengths of the major and minor axes.

%Define the position of the asset:
x0 = 50;
y0 = 50;

% Show the fire front through time, including the position of the asset.
time = 1:2:10;
theta = 0:0.1:2*pi;
clear x y
for t = 1:length(time)
    %clear x y
    for i = 1:length(theta)
        x(i,t) = R0*time(t)*(g + f*cos(theta(i)));
y(i,t) = R0*time(t)*h*sin(theta(i));
    end
end

figure
plot(x,y)
axis equal
legend(['Time = ', num2str(time(1)), ' hr'], ['Time = ', num2str(time(2)), ' hr'], ['Time = ', num2str(time(3)), ' hr'], ['Time = ', num2str(time(4)), ' hr'], ['Time = ', num2str(time(5)), ' hr'])
hold on
plot(x0,y0,'*','MarkerSize', 10)
hold off

% Now, show the power absorption at the point at each timestep

clear time;
time = 1:0.1:10; % Define new time intervals for second graph
for t = 1:length(time)
    int_t = time(t);
    power(t) = H*w*R0*h*quad(@ellipsefun, 0, 2*pi); % Get power by numerical integration.
end

figure
plot(time,power)
xlabel('time (hours)')
ylabel('Power absorbed at asset (kW)')

ellipseefun.m

% This file, 'ellipseefun.m' is called byellipse.m and provides the equation to give the delta of the power at an asset,
% due to the power output at delta theta.

function [power] = ellipseefun(theta)

global H w f g h R0 x0 y0 int_t

t = int_t;

power = H*w*R0*h*(g.*cos(theta)+f).*f.*sqrt(1-(1-h^2/f^2).*sin(theta).^2) ./ (sqrt(h^2.*cos(theta).^2 + f^2.*sin(theta).^2).*((x0 - R0*t*(g + f*cos(theta))).^2 + (y0 - R0*t*h*sin(theta)).^2));