EXPERIMENTAL DEVELOPMENT OF A FIRE MANAGEMENT MODEL FOR JARRAH (*EUCALYPTUS MARGINATA* DONN ex Sm.) FOREST

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DECLARATION OF ORIGINALITY

I hereby certify that the work reported in this thesis is my own except where duly acknowledged.

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SUMMARY

Accumulations of flammable fuel and seasonal hot, dry weather has ensured that fire is an important environmental factor which has shaped jarrah forest ecosystems of south-west Western Australia. Today, fire impacts on all aspects of jarrah forest management, including timber and water production, recreation and wildlife conservation. Fire management involves controlling destructive wildfires and applying prescribed fires over a wide range of burning conditions to achieve a variety of protection, production and conservation objectives. A sound scientific understanding of the behaviour, physical impacts and long term ecological and commercial effects of fire is essential to planning and implementing fire regimes and suppression activities pertinent to current and foreseeable management. Existing forest fire behaviour guides developed in the 1960s from small low intensity experimental fires set under mild conditions perform adequately over the low fire intensity range, but are deficient at predicting the behaviour of moderate and high intensity fires burning under warm, dry conditions. Another shortcoming is that they do not attempt to predict physical impacts of fire which give rise to ecological responses or commercial losses.

This thesis describes laboratory and field experiments designed to model the behaviour and some important physical impacts of fire in jarrah forest over a wide range of potential burning conditions. Fire behaviour and fire impact models were developed for a standard jarrah forest fuel type; the structure, composition, dynamics and combustion properties of which were studied in detail. Most variation in equilibrium headfire rate of spread on level terrain was best explained by the product of a power function in wind speed and a power function in fuel moisture content. Headfire rate of spread was independent of the quantity of fuel per unit area. Forced convection and flame contact appeared to be the primary mechanisms for flame spread in wind driven fires which burnt across then down into the eucalypt litter fuel bed. Conversely, the rate of spread of zero wind fires and backfires was directly related to the quantity of fuel burnt, suggesting that radiation was the primary mechanism for flame spread in this situation. The transition from a fire spreading primarily by radiation to one spreading primarily by convection occurred at a wind speed of 3 - 4 km h^{-1}. For zero wind conditions, rate of spread and slope were best related by an exponential equation form and fire shape was described by a power function in wind speed. Flame size was a function of rate of spread, fuel quantity consumed and fuel moisture content.

Immediate physical impacts of fire on vegetation and soil were examined in three zones and coupled with fire behaviour variables and factors affecting heat transfer by fitted regression models. Impact above the flames (crown scorch height), was dependent on flame height, fire intensity and the season in which the fire occurred. Impacts in the flames (stem damage and mortality), were dependent on the quantity of fuel consumed, fire intensity and bark thickness. Soil heating was a function of the quantity of fuel consumed, soil moisture and fuel moisture. A soil heating index was developed which allows numerical characterisation of fire-induced soil heating. The fire behaviour and fire impact models developed by this thesis provide a scientifically based system for using fire as a tool for multiple use forest management.

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CHAPTER 1

GENERAL INTRODUCTION

1.1 Thesis Introduction

Fire, climate and vegetation have a long association in south-west Australia, one which pre-dates the arrival of Europeans by thousands of years (Gardner 1957, Jackson 1968, Hallam 1975). Prior to European settlement, fires were started by lightning and by Aborigines who used fire extensively from the coastal forests to the spinifex deserts of central Australia (Kessell 1928, Calley 1957, Jones 1969, Hallam 1975, de Graaf 1976, Nicholson 1981 and Kimber 1983). Further evidence of this long association is the evolution of a diverse range of physical and behavioural fire adaptive traits present in populations of indigenous fauna and flora (Ahlgren and Ahlgren 1960, Christensen and Kimber 1975, Gill 1975, 1977, Gill *et al.* 1981, Christensen and Abbott 1989).

A bushfire-vulnerable society settled this fire prone environment when Europeans colonised the Swan River in 1829. Unlike the Aborigines, Europeans built permanent homes and settlements in and around the jarrah (*Eucalyptus marginata* Donn ex Sm.) forest, worked to clear the bush for farms, and exploited the forest for timber. To the early settlers bushfires were seen as destructive, threatening their lives, property and welfare (see Pyne 1991).

Prior to the 1960s, management of the jarrah forest was primarily concerned with wood production but since then, greater emphasis has been placed on other values (Bradshaw *et al.* 1991). Today, the jarrah forest is a multiple use forest catering for a range of demands and expectations. Fire management has evolved to become more complex and sophisticated to meet multiple use management objectives and currently aims to protect life, property, forest values such as timber, ecosystems and biodiversity, landscapes, recreation and amenity values (Christensen 1978, Shea *et al.* 1981, Underwood and Christensen 1981, Underwood 1988, Burrows 1990, Bradshaw *et al.* 1991 and Burrows and Van Didden 1991). Fire management, especially the practise of rotational broad area fuel reduction burning, is also one of the most controversial issues facing jarrah forest managers (e.g. Australian Conservation Foundation 1970, Ealey 1984, Ford 1985, Tingay 1985, Llewellyn 1989 and Shea 1989).

Broad area aerial fuel reduction burning since the 1960s has successfully reduced the impact of wildfires on the jarrah forest and surrounding communities (Underwood *et al.* 1985). Fundamental to the success of fuel reduction burning and to wildfire control generally, are the

"Forest Fire Behaviour Tables for Western Australia" (Sneeuwjagt and Peet 1979, 1985), a fire danger rating and fire behaviour prediction system originally developed in the 1960s (Harris 1968 and Peet 1972).

Using prescribed fire as a biological tool to meet a range of forest management objectives has become increasingly important as fire management expertise and knowledge of fire behaviour and ecology expands. The Western Australian Department of Conservation and Land Management (CALM) administers State forests, nature reserves, conservation forests and national parks and is responsible for fire management on these lands. Appropriate fire management plans have been and will continue to be developed which attempt to satisfy conservation and wildfire protection objectives. These include a range of special prescribed fire regimes, as well as fire exclusion, to meet the varying requirements of specific forest ecosystems (see Bradshaw *et al.* 1991).

Shea *et al.* (1981) proposed a prescribed burning regime for jarrah forests which would result in more diverse ecological systems. In particular, they refer to the use of fire as a possible method for controlling the soil-borne fungal pathogen *Phytophthora cinnamomi* Rands (Podger 1972) in the jarrah forest. They state that this could be done on some sites by using fire to reduce the abundance of the highly susceptible *Banksia grandis* understorey and replacing it with leguminous species which are more tolerant of the fungus. This would:

- create a less favourable physical environment for fungal sporalation;
- favour the development of a soil micro-environment which is antagonistic to *P. cinnamomi*;
- improve forest vigour by increasing soil nitrogen levels.

Christensen (1974, 1977, 1980, 1982, 1991) and Christensen *et al.* (1981) have proposed a fire regime for managing and assisting with the recovery of the now rare and endangered Tammar wallaby *(Macropus eugenii)*, which at one time inhabited much of the eastern jarrah forests and woodlands of the south-west of Western Australia. This regime incorporates an appropriate sequence of low intensity fuel reduction fires, to protect extant populations from large and intense wildfires, and occasional high intensity early autumn fires to regenerate thickets of *Melaleuca viminea* and *Gastrolobium bilobum* which form vital habitat for the wallaby.

Burrows (1990) proposed a fire regime for northern jarrah forests which consists of varying both the season and periodicity of fires to achieve protection and conservation benefits. There is also mounting evidence that burning under summer or early autumn weather conditions to induce full crown scorch may disadvantage the serious insect pest, jarrah leafminer (*Perthida glyphopa*) (Mazanec 1989 and Abbott *et al.* 1993).

In order to plan and implement appropriate fire regimes to achieve the type of management objectives described above, fire scientists and fire managers need to accurately and consistently predict:

i) fire behaviour (for wildfire control and for prescribed burning),

ii) the physical impacts of fire which give rise to desired fire-induced ecological responses,

iii) the physical impact of fire on forest values, especially timber.

That is, in addition to predicting fire behaviour reliably over a wide range of conditions, a jarrah forest fire model must also couple fire behaviour characteristics to the immediate physical impacts, or acute impacts of fire of concern to fire ecologists and fire managers.

Managers need descriptive and quantitative information about the type of fire needed to achieve a desired ecological response or impact, and the conditions of fuel, weather and topography to achieve the desired fire behaviour. They also need to be able to quantify a fires impact on other forest values, such as timber. It is not sufficient to describe a fire as "hot" or "cool" when attempting to implement a prescribed fire to achieve a set ecological objective such as to regenerate a specific plant species or to fully scorch the forest canopy. It is important to identify and describe fire in meaningful ways in order to understand and to anticipate the ecological outcome and to evaluate its impact on plants, including commercial tree species. For example, Peet and McCormick (1971), Christensen and Kimber (1975), Shea and Kitt (1976) and Shea *et al.* (1979) have observed that intense summer or autumn fires are necessary to regenerate legume thickets in the jarrah forest on most upland sites. However, this correlation between fire intensity and legume regeneration may not be causal and may simply reflect limitations in understanding and describing energy release and heat transfer.

Two models are used to estimate fire danger and to predict fire behaviour in Australian eucalypt forests. The McArthur Meter (McArthur 1973) is used in the eastern Australian states and the Forest Fire Behaviour Tables for Western Australia (FFBT) (Sneeuwjagt and Peet 1979, 1985) are used in the jarrah forests of Western Australia. Both models were empirically derived in the 1960s, although FFBT have been continually modified and updated in the light of new research findings (the most recent edition of FFBT incorporates some of the fire behaviour findings reported in this thesis). Using prescribed fires to achieve the ecological responses described above requires fires to be set under warm dry conditions in autumn or summer. Fire researchers and managers in Western Australia were concerned that the existing fire behaviour models would not perform adequately under these conditions.

Observations of summer and early autumn wildfires in eucalypt forests revealed that the actual rate of spread of fires was often 2-3 times faster than predicted by the existing models. Fire managers were not confident that they could safely prescribe fires under warm, dry conditions, or accurately predict the rate of spread of summer wildfires based on the existing models which were developed from very small, point ignition experimental fires set under mild weather and fuel conditions. In addition, the existing models do not provide a measure of the likely variability of fire behaviour for a given set of conditions. They were not developed from functional relationships and have a limited statistical basis.

As well as fire behaviour prediction limitations, Australian fire models were not designed to predict or describe the ecological characteristics or physical impacts of fire beyond estimating scorch height. The FFBT make no attempt at predicting energy release and heat transfer nor do they couple fire behaviour and fire impact on plants and the soil which is essential for understanding how fires produce various physical and ecological responses in the jarrah forest. Because current fire behaviour prediction models do not describe fire adequately enough to enable ecological responses to be interpreted or predicted, they are inadequate as a basis for applying fire to produce a desired ecological outcome. Changing forest and fire management objectives demand more comprehensive fire models. Johnson (1992) has recently attempted to couple four characteristics of fire behaviour to their effects on boreal tree populations in North America but there are no applied fire models which fulfil this purpose for Australian eucalypt forests.

1.2 Thesis Aims

Australian eucalypt fire models were developed in the 1960s primarily to meet the fire management objectives of the day; to provide a means of rating forest fire danger, to estimate the spread of wildfires and to facilitate the safe and efficient implementation of low intensity fuel reduction burns under mild weather conditions. A detailed description of the development, application and limitation of existing eucalypt fire behaviour models is presented in Chapter 4.

Pioneering work by McArthur (1962) and Peet (1972) laid the foundations for understanding and predicting fire behaviour in the jarrah forest where they studied the behaviour of small, low intensity fires lit from a point source under mild weather conditions (see Chapter 4). The research presented in this thesis builds on this research by re-examining some of the relationships they developed and by studying the behaviour and impact of larger and more intense fires burning in drier fuels and under windier conditions.

Plate 1a - 1d: The jarrah forest is managed for many purposes including wood (Plate 1a), water (Plate 1b), wildlife (Plate 1c). Fire impacts on all aspects of management.

Plate 1a: Wood production

Plate 1b: Water production

Plate 1c: Wildlife conservation (Photo T. Leftwich)

A fire model capable of predicting i) fire behaviour over a wide range of burning conditions and ii) physical impacts of fire is necessary for developing sound fire management objectives and for effective application of strategies. A reliable fire behaviour prediction system is essential for wildfire control and for setting prescribed fires under dry fuel conditions when there is a high risk of extreme fire behaviour and fire escape. It allows fire managers greater scope and confidence in planning and executing wildfire pre-suppression and suppression operations and in using fire as a management tool to achieve a range of ecological objectives. It is not possible to address all the fire responses which are likely to be important in the future, but a model which allows fire behaviour to be predicted over the range of fuel and weather conditions possible in the jarrah forest environment is fundamental to achieving any management objective.

This thesis describes the experimental development of a statistically-based fire management model for current and anticipated management of the jarrah forest of Western Australia. Specific aims are:

1. To model the behaviour of low and moderate intensity (<5,000 kW m^{-1}) fire in jarrah forest fuel (standard jarrah forest fuel). Fire behaviour variables of interest are;
   - i) fire rate of spread
   - ii) flame height and flame length
   - iii) flame residence and burn-out time
   - iv) fire intensity
   - v) flame temperatures and temperature histories
   - vi) fire shape.

   Data gathered from experimental fires set in the laboratory and in the field are used to develop a jarrah forest fire behaviour model.

2. To develop predictive models which couple fire behaviour variables, factors affecting heat transfer, and physical impacts of fire on vegetation and soil. Physical impacts of interest are those which cause damage to timber species and those which give rise to the ecological effects relevant to current and the foreseeable management of the jarrah forest. Such an understanding is vital when interpreting fire effects and when fire is deliberately used to manipulate elements of ecosystems to achieve defined ecological objectives.

The immediate physical impact of fire on vegetation and soil is considered by this research to occur within three zones:

1. The zone above the flames where leaves and fine twigs are killed by convected heat (scorch).
2. The zone within the flames where leaves and fine twigs are consumed by the flames and stems are killed or injured.
3. The zone beneath the flames where soil and soil organisms are heated.

The general structure of the fire model is shown diagrammatically in Figure 1-1 below.

1.3 Thesis Structure

The thesis is presented in 13 Chapters. Definition of terms and symbols used are contained in a glossary (Appendix 1). In most instances, analysis of variance tables for the various regression models developed throughout this thesis are contained in Appendix 2.

Chapter 2 briefly describes biophysical elements of the jarrah forest and the setting in which the fire model is developed.

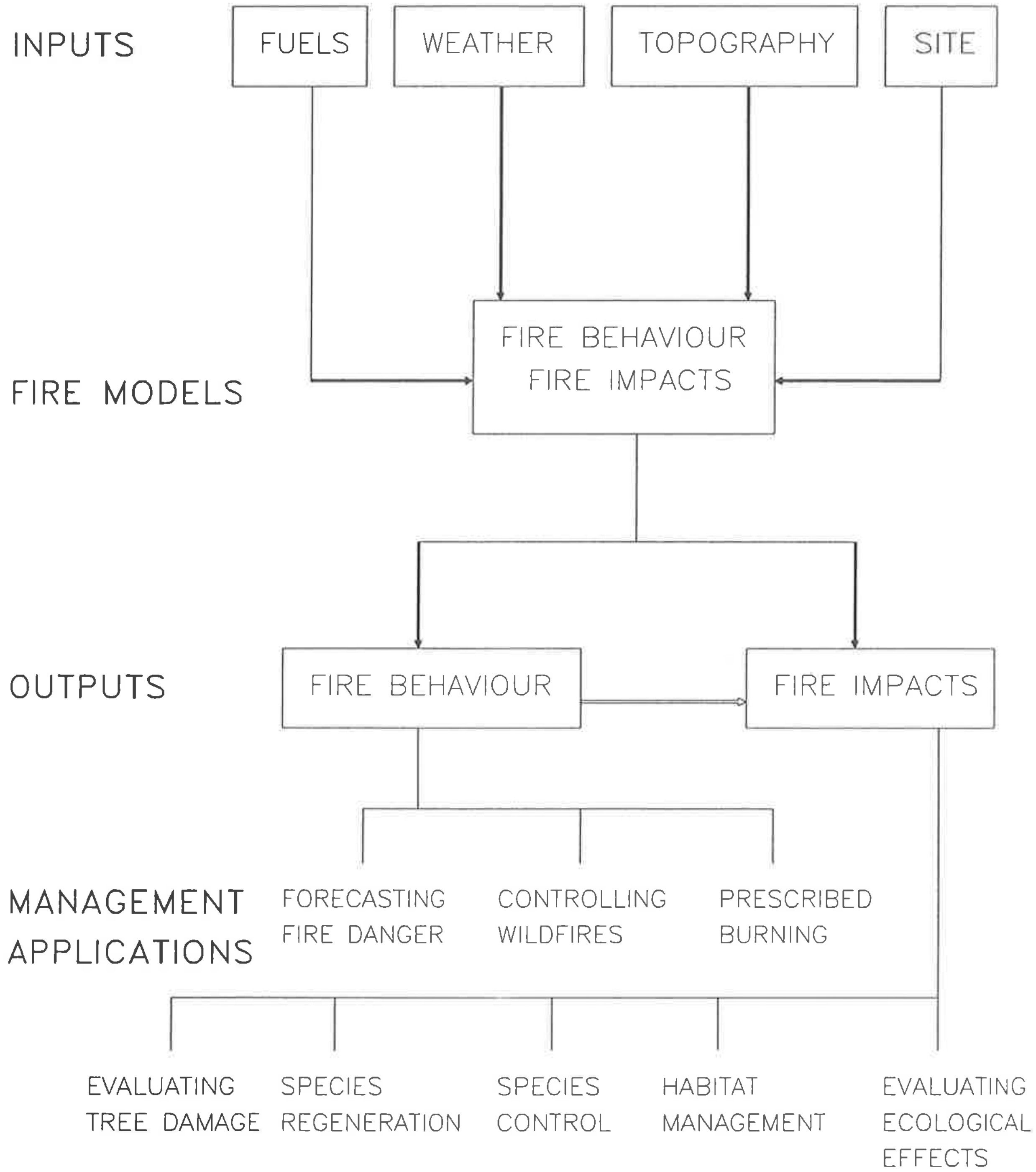
Chapter 3 reviews the management history of the jarrah forest, including fire management, describes current and foreseeable fire management objectives and emphasises the importance of fire as a natural factor which impinges on all aspects of jarrah forest management.

Chapter 4 reviews the various world-wide approaches to modelling fire behaviour with an emphasis on the development of Australian eucalypt forest fire models. The limitations of existing models are discussed which serves to highlight the contribution of this thesis.

Fuel fundamentally affects forest fire behaviour, impact and hence fire management. Chapters 5 and 6 examine the characteristics, dynamics and combustion properties of jarrah forest fuel for which fire behaviour and impact models are developed in later chapters.

The experimental development of an applied jarrah forest fire behaviour prediction model is described in Chapters 7 and 8. Data from laboratory and field experiments are used to develop statistically based functional relationships between dependent (fire behaviour variables) and independent (fuel, weather and slope) variables.

Figure 1-1: Structure of the jarrah forest fire model.



Chapter 9 is an overview of the physical impacts of forest fire and introduces an investigative framework for physical impact modelling in the jarrah forest situation. Chapters 10, 11, and 12 deal with modelling acute physical impacts of fire on vegetation and soils which are relevant to contemporary jarrah forest management. These chapters examine physical impacts in the three zones described above. Quantifiable measures of impact are coupled with fire behaviour variables and factors affecting heat transfer. An ability to predict crown scorch (Chapter 10) is important for implementing low intensity fuel reduction burns where the aim is to maintain scorch height below 6 m. On the other hand, prescribed fires to induce seedfall or to impact on the insect pest jarrah leafminer, aim to fully scorch the tree crowns.

Chapter 11 investigates temperature histories in the flaming zone and at the cambial layer of bull banksia stems, and discusses fire-caused damage to the boles of jarrah trees. Fire behaviour descriptors which best correlate with temperature histories and stem damage are identified and predictive models of fire-caused stem mortality and damage are developed.

Prescribing fire to regenerate legume thickets beneficial to forest health or for wildlife habitat, while minimising damage to trees, requires an understanding of factors affecting heat transfer to the soil. Chapter 12 investigates relationships between soil heating, soil moisture, fuel and fire behaviour variables in the laboratory.

The various fire behaviour and impact model components developed in the preceding chapters are assembled into an integrated, applied jarrah forest fire model in Chapter 13. The scientific and management contributions of this research are summarised and key areas requiring further research are identified.

Plate 1-2: Aerial ignition of a low intensity fuel reduction burn in jarrah forest.

CHAPTER 2
THE JARRAH FOREST

2.1 Description

The jarrah forest ecosystem is unique to the south-western corner of Western Australia (Figure 2-1). Prior to European settlement jarrah forest covered some 5.3 million hectares but land clearing for agriculture has restricted its distribution to about 3.3 million hectares (Dell and Havel 1989). The jarrah forest occurs from about east of Perth in the north to Albany in the south, where annual rainfall ranges from 750 mm to 1400 mm. The main forest belt lies to the west of the 600 mm isohyet with stands reaching best development in the high rainfall zone close to the Darling Scarp (Dell and Havel 1989) on the highly leached soils of the Darling Plateau which forms the south-western portion of the Great Plateau of Western Australia (Jutson 1934, Churchward and Dimmock 1989). In the northern part of its range it occurs on an extensively laterised landscape. The terrain is mostly gently undulating with steep slopes associated with deeply incised valleys of major rivers such as the Murray. Detailed descriptions of landform and soils are provided by McArthur *et al.* (1977), Churchward and McArthur (1980), Churchward and Dimmock (1989) and Dell *et al.* (1989).

The pale green trees and shrubs form a dry sclerophyll forest. Based on canopy cover and height, the forest is described as open forest in the north and east and tall forest in the south (Specht *et al.* 1974). Jarrah is the dominant overstorey species, but on some sites marri (*Eucalyptus calophylla* Lindl.) is a co-dominant species. On the best sites, trees may reach a height of 30-40 m and a diameter of 2 m, but more commonly the height of the mature forest is 25-30 m. Mature trees have straight boles up to 12-15 m covered with a persistent thick grey stringy bark. Jarrah is well adapted to survive fire; its thick bark (up to 30 mm) protects the bole, and the tree is able to resprout from a below ground lignotuber or from epicormic shoots. Detailed descriptions of its morphology and biology are given by Abbott and Loneragan (1986).

The forest understorey is floristically and structurally diverse in response to edaphic and climatic factors (Havel 1975) and to fire. In terms of area the largest stands occur on the lateritic uplands where the understorey consists of small trees (4-7 m tall) and a low, sparse ground cover of woody shrubs (up to 2 m). As with jarrah, understorey plants display a range of adaptive traits which enable them to persist in a fire-prone environment (Christensen and Kimber 1975). Fuller descriptions of the floristic and structural diversity of the forest are given by Heddle *et al.* (1980), and Bell and Heddle (1989). The forest contains some 784 vascular plant species (Bell and Heddle 1989), 150 species of native birds and 29 species of native mammals (Nichols and Muir 1989), many of which are endemic.

Figure 2–1: Main jarrah forest belt in the south-west of Western Australia.

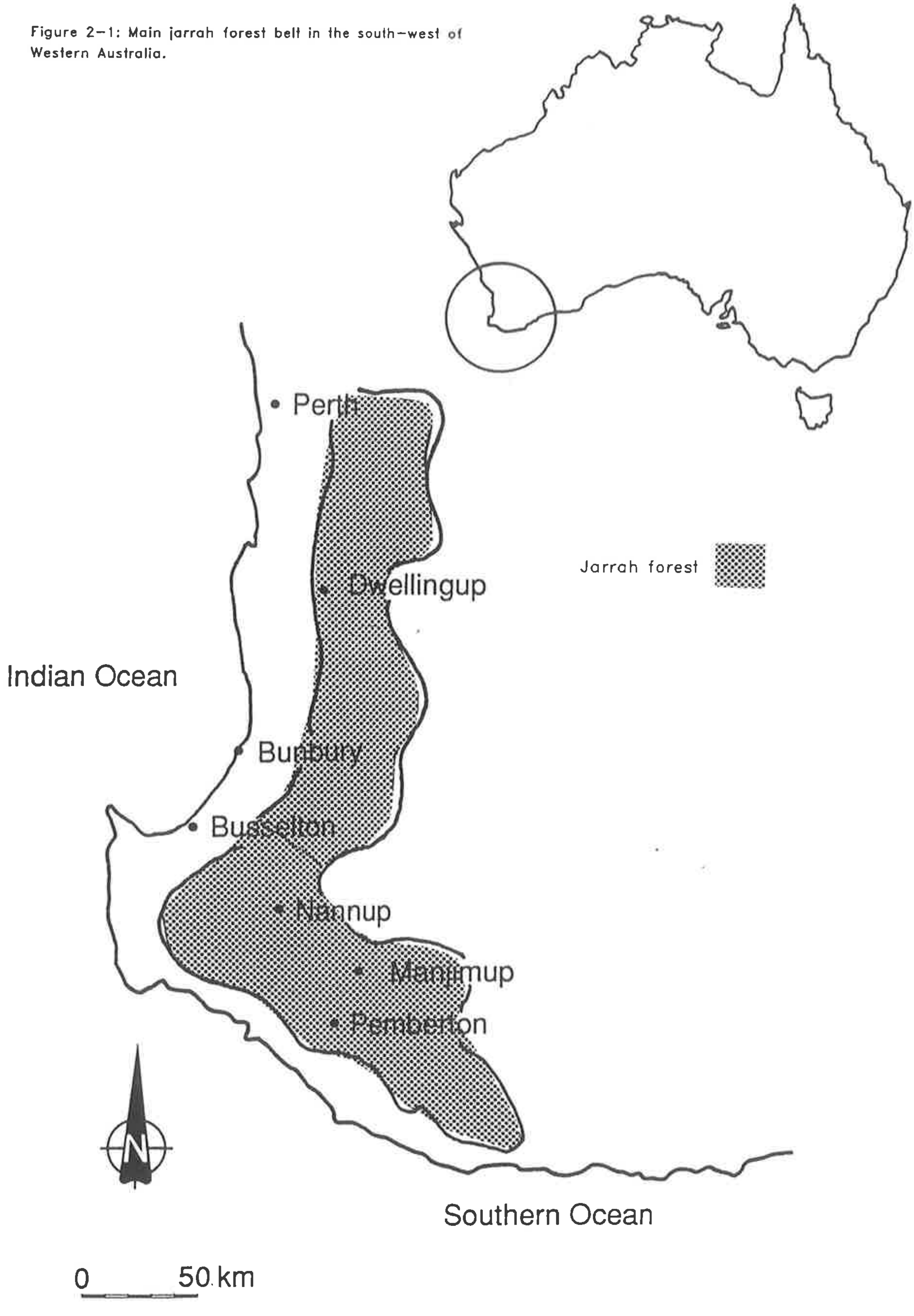


Plate 2-1: High intensity summer wildfire (~ 7,000 kWm^{-1}). About 300 wildfires occur each year in south-west forests.

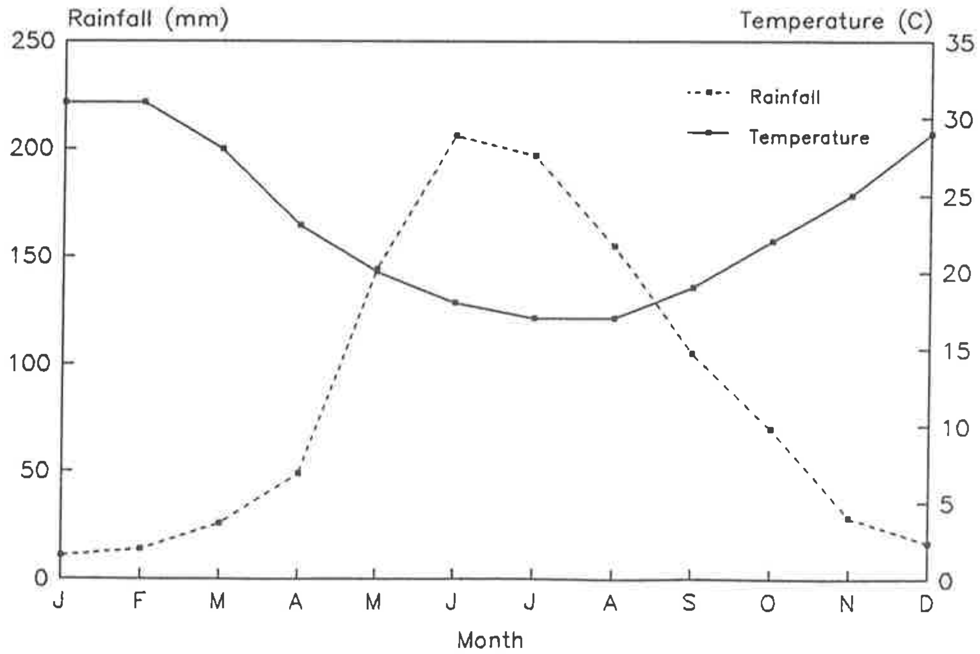
Plate 2-2: Jarrah forest 3 weeks after an intense wildfire. The understorey is totally defoliated and the overstorey is fully scorched.

Plate 2-3: Two years after an intense wildfire. Note the blackened, charred bark on the boles of jarrah trees and the vigorous regeneration of understorey species.

2.2 Fire climate

The climate of the region is conventionally described as mediterranean-type, with cool, wet winters and warm to hot dry summers. The winter rains fall from mid-autumn to mid spring (mid-April to October) (Gentilli 1989). Mean annual rainfall generally decreases with distance from the coast. The mean monthly rainfall and maximum temperatures for Dwellingup, a station in the high rainfall zone of the northern jarrah forest, are shown in Figure 2-2. The region experiences a seasonal drought which may last from 4-6 months (November to March) (Gentilli 1989), which, together with accumulations of flammable fuel, predisposes the jarrah forest to an annual season of fire outbreaks.

Figure 2-2: Mean monthly rainfall and temperature for the town of Dwellingup, W.A., located in high rainfall jarrah forest. (Source: Hall et al. 1981)



The climate is dominated by a succession of high pressure systems which move from west to east. During the winter months they bring cool moist air to the region and regular rainfall during this period normally ensures that the forest fuels are too wet to carry fire. The anticyclones track further south with the onset of spring and summer and warmer drier air results in the gradual drying of forest fuels from about September to December. It is during this period that about 200,000 ha of forest are prescribed burnt each year by low intensity fires to minimise the impact of wildfires; a practise that was initiated in the late 1950s by the Western Australian Forests Department and became widespread in the 1960s following the severe "Dwellingup wildfires" of 1961. Warm to hot, dry conditions usually persist over the summer and early autumn months, with only occasional showers of rain. This is the period of frequent wildfire outbreaks; about 350 each year.

An examination of mean sea level synoptic charts for several summers reveals a regularly repeating sequence of events which determines the fire weather experienced in the jarrah forest region. This sequence has been idealised as follows (from the Bureau of Meteorology, Perth).

Day 1: A trough of low pressure, which separates two high pressure cells, forms inland from the west coast. The trough line marks a change of wind direction from north-east on the eastern side of the trough to south-east on the western side. Temperatures are high and relative humidities and fuel moisture contents are low over most of the jarrah forest region. Unstable conditions along the eastern edge of the trough often result in thunderstorms and lightning. Afternoon sea breezes frequently bring cooler air some distance inland. Near the coast, these breezes can be quite strong, creating fire control difficulties.

Day 2: The trough line moves slowly inland, as an advancing ridge of high pressure forces cooler, moist oceanic air through the jarrah forest region. East of the trough temperatures remain high and humidities low. The timing of the trough line movement is difficult to forecast but is of considerable interest to fire management agencies because it is accompanied by a significant change in wind direction, temperature and humidity. This can create particularly serious wildfire situations if there have been multiple lightning strikes originating from thunderstorms along the trough line. In some instances, the eastward movement of the trough is accompanied by strong north-west winds mixed down to the surface from higher altitudes. Severe wildfires have often been associated with these conditions.

Day 3: The ridge of high pressure extends eastward and a high pressure cell forms to the south of the State. Winds over the jarrah forest region have shifted from south-east to east, with late afternoon weak sea breezes along the west coast. Maximum temperatures throughout the region are starting to rise.

Day 4: The cell of high pressure to the south of the State is cut off by a developing trough to form two cells. Hot, dry north-east winds are experienced over most of the region. A trough of low pressure forms off the coast and the cycle is repeated.

Various meteorological phenomena can modify this idealised sequence and affect fire weather in the region. These include i) moisture in the air at levels below 6,000 m which may result in rain, ii) the development of a closed low in the northern end of the trough, iii) intensification of an anticyclone south east of the State and iv) tropical cyclones. A tropical cyclone crossed the south-west corner of the State in April 1979 and the warm, dry conditions and gale force winds created a potentially severe fire situation. There were mass fire outbreaks throughout the south-west and if it had not been for extensive prior fuel reduction burning over a number of years, and prompt and efficient suppression action, a wildfire disaster would not have been averted.

CHAPTER 3

HISTORY OF JARRAH FOREST FIRE MANAGEMENT

3.1 Introduction

A review of the history of fire management in the jarrah forest serves to explain current fire management and research and demonstrates the imperative linkages between culture (of society at large and of fire management agencies), government policy, agency goals, management strategies and technology. It also demonstrates how fire impacts on all aspects of jarrah forest management including timber production, water production, conservation values, etc. and the management need for reliable fire models.

Since European settlement, controlling wildfire and prescribing fire to achieve management objectives have been high priorities. Whatever the management objectives, past and future, a sound scientific knowledge of fire behaviour, and of ecosystem response to fire, is essential for modern forest management in a fire prone environment.

Fire management in the jarrah forest has advanced considerably since 1916 when the colonial forester Hutchins declared that "few Australians will admit that fire protection of the forest is practicable". Since 1918 the scope of fire management has progressively expanded to accommodate the increasingly complex demands placed on forests by society. Initial concerns about protecting human life and property from wildfire soon expanded to include protection of the forest timber resource. Today, forest fire managers are increasingly being called upon to integrate fire, an important natural environmental factor, with a wide range of activities and resources including recreation, water production, fauna and flora conservation, disease management and maintenance of landscape amenity. Fire management practices must also be modified to accommodate the major changes in the structure and species composition of some areas of forest as a result of human activities such as logging and mining.

While fire management has been an evolutionary process, an overview of the history of fire in the jarrah forest can be presented by cultural eras which are essentially bounded by changes in community attitudes and forest utilization.

3.2 The first European era: 1829-1918

The Swan River Colony was first settled by Europeans in 1829. One of the main attractions of the new colony was the vast expanses of forest and the great demand for suitable ship building timber by the Royal Navy (Wallace 1965). In 1836, about 10,000 tonnes of Swan River mahogany (jarrah) timber was sent to the naval dockyards in England (Ednie-Brown 1896). The English oak forests had been decimated and timber supplies from the newly independent America were not readily available to the Royal Navy (Wallace 1965).

Uncontrolled exploitation of the forest continued for the next 90 years after settlement (Lane-Poole 1921). By 1918, some 500,000 hectares of the jarrah forest had been cut-over and 17 million tonnes of logs had been removed, resulting in a 50% reduction in the forest canopy (Wallace 1965).

Non-merchantable logs and tops of trees were left behind on the forest floor, adding around 40 t ha^{-1} of additional fuel (Wallace 1965). The quantity and nature of the fuel resulting from heavy logging operations was unprecedented in the history of the jarrah forest. In the past, regular burning by Aborigines and lightning-caused fires had kept the litter and scrub fuel accumulations low (Kessell 1928, Harris 1961, Wallace 1965, Hallam 1975, Underwood 1978, Hallam 1985 and Christensen and Annells 1985). Descriptions of forests by early settlers support the argument that the jarrah forest had been burnt by frequent, low intensity fires over thousands of years (Bunbury and Morrell 1935, King 1963, Hallam 1975, and Pyne 1991). These mild fires, burning in relatively light fuels, would have caused little damage to the boles and crowns of trees. There is no record of any significant fire-caused timber defect in logs which went through the early sawmills. However, in the early years of settlement, no-one was charged with the responsibility of managing the forest or controlling the sawmillers. No action was taken to dispose of the heavy accumulation of debris left in the wake of sawmilling operations. Uncontrolled fires broke out and they were far more intense and devastating than any that had ever been experienced (Kessell 1920, Anon. 1922, Stewart 1951).

In the early days, there was little concern about wildfires. They were small and of little consequence in relation to the seemingly limitless forest resource. In fact, wildfires provided a spectacle to the early settlers, many of whom found the jarrah forest rather "dull and uninteresting". In 1847, George Webb reported in the Swan River News; "The bright flames surrounding the trunk of a lofty tree, and finally seizing on the branches, boughs and leaves was a very beautiful spectacle". However, as settlers spread farther into the forest, there was some concern about the potential destruction of settlements by forest fire. In 1847, the first Bushfires Ordinance provided for "aborigines and minors" to be fined or publicly flogged for lighting fires.

Landowners were exempt and were able to light fires on their own land whenever they pleased. Naturally, many of the settler's fires escaped into the forest and often burnt uncontrolled for many days.

Around the turn of the century, foresters and the community at large were becoming increasingly alarmed at the devastation caused by uncontrolled wildfires (Ednie-Brown 1896). Many thousands of hectares of young regrowth forest replaced the mature forest which was being cut at a staggering rate. Early foresters saw that wildfires were injuring seedlings and saplings and causing faults and defects in the timber (Richardson 1910). Others believed that if fire could be excluded from the forest then not only would the young regrowth be protected, but soil fertility would improve and the growth and timber yield would be greater (Richardson 1910, Hutchins 1916). The policy of the then Woods and Forests Department, with its meagre resources, was to confine wildfires to the smallest possible area by using a system of firebreaks (Richardson 1910). However, the rapid expanse of cutting and indiscriminate burning made it virtually impossible to control wildfires.

It was strongly argued (Hutchins 1916, Anon 1922) that fire prevention was achievable and was the only way of stopping the wildfire menace. Changes to the Bushfires Act in 1885 allowed the Governor to impose prohibited burning times. Further legislation and amendments to the Act in 1902 specified the conditions under which fires could be lit including the requirement for firebreaks, notification of neighbours and the need to "keep at least three men in attendance". It was also necessary to hold a "Permit to Burn" before setting fire to bush which had been declared a fire protected area by the Minister for Lands. Breaches of the Act could incur fines of up to fifty pounds (Anon. 1927). However, wildfires could not be outlawed and intense fires continued to burn throughout the jarrah forest.

In the early part of this century, there was a small but growing band of advocates for a return to the traditional Aboriginal practice of frequent burning of the forest. They believed that this could be achieved in virgin forest where fuel loads were considerably lower and trees were larger and able to withstand "light" burning. Heavy fuels in young regenerated forest would be difficult to burn without injuring the small trees. There was some opposition to the practice of frequent light burning on the grounds that it caused "soil sickness" and poor tree growth. Hutchins (1916) forcefully argued that total protection from fire could be easily afforded to Australian eucalypt forests.

He was "disturbed by the number of people in Australia who promoted the idea of frequent burning of the forest to reduce the wildfire hazard". Kessell (1920) also drew upon his European forestry experience to make a case against the frequent use of "creeping" fires to control wildfires. He argued that such a practice would deplete the soil of vital nutrients and eventually "destroy every vestige of humus and slow the growth rate of the trees". In any event, the resources of the then Woods and Forests Department, later the Forests Department, were so meagre, and the fire problem so enormous, that broad acre fuel reduction burning was not possible.

3.3 The second European era: 1918-1954

As the forest became more fragmented by towns, farmlands and sawmilling operations, the community and politicians became concerned about the lack of forest conservation and protection. After 70 years of settlement there was a slow realization that the forest resource was finite and that uncontrolled cutting and the ensuing wildfires were not only destroying valuable timber, but were a threat to human life and property.

In 1918, the passing of the Forests Act and the formation of a Forests Department were the first steps towards deliberate forest protection and management. Wallace (1965) wrote "Faced with the scarred and blackened boles of cut-over areas and the grossly malformed stems of the young second growth trees, together with the mass of scrub and weed trees on one million acres of cut-over forests, the newly appointed foresters found themselves with staggering problems in both fire protection and silviculture". The first Conservator of Forests, Lane-Poole (1921), also despaired that "unless measures were taken to increase stocking levels and protect the young trees from fire, there would be no timber for future generations".

The new Forests Department developed a three pronged management strategy. The first task was to protect the virgin jarrah forest from fire. Secondly, debris resulting from current falling operations (extending at a rate of 20 000 ha annum^{-1}) needed to be removed or reduced. The third task was to rehabilitate the thousands of hectares of forest cut over in the last century and protect them from wildfire. During the first few years, lack of experience, confidence, knowledge and resources restricted the effectiveness of the enthusiastic foresters. However a cohesive plan of action emerged. The northern jarrah forest was categorized and mapped according to whether it was virgin forest, regrowth forest or non-forested "bush" which was of little commercial value. A fire management plan was developed for each of these categories. In the young regrowth forest, "Zone A", fire was excluded. In older regeneration, low intensity fires were set in the cooler, moister time of year to reduce fuel loadings (O'Donnell 1939). In "Zone B", where the virgin mature forest awaited cutting, low intensity fires were prescribed under mild weather conditions and as frequently as possible (3-4 years). The total area of forest burnt in this way each year is not well documented between 1918-1925, but it was probably a small proportion of forest in

"Zone B" given the limited extent of fire behaviour knowledge, experience and resources. The sub-marginal or non-commercial forest and unforested heath and wetlands constituted "Zone C". These areas were burnt as frequently as possible and little effort was made to suppress wildfires. By contrast, in "Zone A", the regrowth forest, every effort was made to suppress wildfires (O'Donnell 1939).

Wildfire protection depended on fire prevention, firebreaks, early detection (look-out towers) and organised fire suppression. Fuel reduction burning was limited because of a lack of confidence in being able to safely and effectively prescribe fire and because resources were meagre (Lane-Poole 1921, Brockway 1923, Rodger 1961). Eventually, the cause of many of the problems associated with jarrah forest management, the sawmilling industry, was slowly brought under some form of control. The most intense and devastating fires were associated with logging, so control of these operations was essential. Felling operations for each sawmill permit were confined to annual cutting coupes. Prior to felling, the coupe was prescribed burnt to reduce the total quantity of fuel and to improve access and visibility. Trees were marked for removal by a forest officer. Tops (tree crowns) and unmerchantable logs were cleared away from the standing trees (Anon. 1927). The tops were burnt in cool weather soon after logging. With an advance burn (prior to logging), tops disposal burns could be conducted with less difficulty. The newly logged and burnt area was then given "Zone A" protection status to allow the regeneration to develop. The early Foresters Manual (Anon. 1927) gives clear instructions as to how and when these tasks were to be carried out. Forest which had been cut over in the last century was compartmentalized into 200-400 ha units. Compartments were surrounded by a mineral earth break constructed by a horse drawn scraper (Anon. 1927). Often, 200 m wide strips of forest or "firebreak belts" were burnt frequently to separate the compartments. No prescribed burning was done inside the compartments for the fear of damaging the young trees. Consequently, as the fuel quantity inside the compartments steadily increased, the difficulties and risks of burning adjacent to the compartments also increased. Early fire control operations concentrated on the northern portion of the jarrah forest range where sawmilling, colonization and land settlement were most active.

Limited control burning to reduce fuel loadings, together with efficient fire detection and communications systems, were seen as vital components of a sound fire control organisation. The importance of a good local knowledge of the bush and an ability to suppress wildfires while they were small was stressed in an early "Foresters Manual" (Anon. 1927). Fire look-out towers were erected first in the Mundaring district, in the hills east of Perth, and by 1965 some 38 towers covered the entire State forest (Wallace 1965). The towers and district offices were linked by "bush telephone" lines and heliographs were used for communicating with fire gangs working in the forest (Anon. 1927, Milesi 1949).

Motorized fire fighting units were introduced in 1934. The first of these, modest by today's standards, carried several pack sprays, fire rakes, saws, axes etc. and 75 litres of water. About the same time, formal training of fire crews commenced. More and better roads, better public liaison and continually improving communication systems (radio) vastly improved the Forests Department's ability to combat wildfires.

Heatwave conditions resulted in devastating forest wildfires in 1933, prompting foresters to examine more closely the relationship between wildfires and weather. The frequent wildfire outbreaks under hot, dry conditions were beyond the control capabilities of the Forests Department. Early attempts at controlled burning (for fuel reduction) often escaped or caused extensive damage on days when weather conditions were misjudged (Milesi 1949). To improve an understanding of how forest fire behaviour and weather variables related, and to improve weather forecasting, a fire weather research station was established at Dwellingup in 1934. The research aimed to i) find a simple measure of fire danger at any time; and ii) explore the possibility of forecasting fire weather.

Fire weather research at Dwellingup followed along the lines of Gisborne (1928) and Stickel (1931). It involved identifying weather variables which affected forest fuel "flammability" (dryness). Researchers attempted to find physical integers of "fire weather" variables, that is, to find a material with similar moisture gain and loss properties as the leaf litter on the forest floor. A range of "surrogate fuels" were tested. The most responsive to weather variables affecting fuel moisture, hence flammability, was a 12 mm diameter pine (*Pinus radiata*) cylinder. A strong correlation existed between the moisture content of the pine rods (or hazard sticks) sheltered in a weather screen and fire hazard rating. By weighing the pine rods to determine their moisture content, the fire hazard could be rated as LOW, MODERATE, AVERAGE, HIGH, SEVERE or DANGEROUS (Wallace 1965, Hatch 1969).

The pine rods worked reasonably well as a qualitative measure of fire hazard. The most serious problem with the rods was weight loss due to weathering and bio-degradation as well as moisture loss. This was partially overcome by regularly replacing the rods. A crude relationship between fire hazard, fire behaviour, temperature and relative humidity was developed and became the basis for fire control operations throughout State forest (Wallace 1936).

For 20 years after the Dwellingup fire weather research station was established, the accuracy of weather and fire hazard forecasts steadily improved. Together with increasing experience and growing resources, more area of forest came under fire management. Firebreaks were constructed around regrowth forest, more areas of virgin forest were control burnt and tops disposal was keeping pace with sawmilling operations. However, there were still many thousands of hectares of forest that were not managed to minimise wildfire damage.

From 1944 to 1964, some 300 wildfires burnt each year in W.A forests (Wallace 1965). The cause of wildfires (mainly human) varied over the 20 year period, but Wallace (1965) reported that escapes from Forests Department control burns were one of the main causes, together with mill locomotives and escapes from clearing burns on private property. Escapes from departmental control burns (when the conditions were "misjudged") were usually quickly suppressed, as these fires were set under cool, moist conditions in spring. However, it was a concern for fire control officers of the day. O'Donnell (1945) expressed his concern about the risks associated with control burning, particularly in forest areas which had not been burnt for many years and which carried heavy fuel loadings. He was also concerned that the Forests Department could not afford fire management to a greater portion of forest, but could only protect cutting coupes, regrowth forest and forests adjacent to settlements. Control burning prior to the mid 1950s amounted to burning strategic strips around forest compartments. The high risks associated with burning areas carrying heavy fuels meant that such areas could only be safely burnt under very cool, mild weather conditions. This reduced the number of days when control burning could be carried out. At this time, control burning was conducted by bush crews on foot or horseback. Using this technique, the total area burnt each year was considerably less than what was desirable. Forest managers were falling behind their self-determined protection program. Fuel loadings steadily accumulated in the many thousands of hectares of forest compartments which were protected from fire.

Protecting forest compartments from fire using a fire break system was failing. Following extensive and devastating wildfires in 1949 and 1950 (Wallace 1965), it was clear that, with their meagre resources, fire fighters could not control wildfires over more than one million hectares of forest.

3.4 The third European era: 1954-1976

In 1954, a new fire management policy was developed. Instead of attempting to minimise wildfire damage using firebreaks and strategic fuel reduction burns, it was decided that broad area fuel reduction burning should be attempted. This change brought a complexity of new problems. The most serious of these was the question of how to safely control burn vast areas of forest which had not been burnt for upwards of 25-35 years. Not only were there heavy accumulations of fuel but the forest regrowth could be damaged. If most of the State forest was to be burnt every 5-10 years (depending on the rate of fuel accumulation), almost 200,000 ha would have to be burnt each year - a daunting task for several hundred people charged with forest fire management.

Wallace (1965) calculated that each person must prescribe burn 1,125 ha each year; there were only about 45 days each year which were suitable for control burning.

In January 1961, there were multiple wildfire outbreaks near Dwellingup as a result of 22 lightning strikes in 24 hours. Under the hot, dry and windy conditions, the conflagrations burnt about 150,000 ha of forest in four days, and destroyed a number of mills, homes and farms (McArthur 1961b). Amazingly, no human lives were lost. Most of the forest engulfed in the wildfires had been recently cut over and carried regenerating sapling and pole size jarrah (Wallace 1965).

Many thousands of hectares of forest were defoliated and countless tree boles were damaged. Smaller trees were killed back to ground level. Jarrah is well adapted to survive fire and Wallace (1965) reported that within 3-4 years, defoliated forest areas had recovered remarkably well. However, Peet and Williamson (1968) reported heavy commercial losses due to timber degradation as a result of the high intensity wildfires. Some 70,000 ha of forest burnt by wildfire were rated as being relatively undamaged in that upper canopy leaves were not scorched and tree boles were not injured. Field assessments revealed that most of the undamaged forest had been subjected to control (fuel reduction) burning in the previous two years (Wallace 1965, Peet and Williamson 1968). The value of fuel reduction in minimising the impact of wildfires was clearly demonstrated.

Following the Dwellingup Fires of 1961, and the subsequent Royal Commission, the Forests Department reassessed its fire control practices. Foresters felt they had failed in their bid to control wildfires and spurred on by the recommendations of the Royal Commission into the 1961 bushfires, expanded their fuel reduction burning program and their ability to detect and suppress wildfires. Forest fire research effort was stepped up at Dwellingup in order to develop more reliable forest fire danger rating and behaviour prediction systems. Better fire prediction was necessary for planning and safely implementing fuel reduction burns over a larger area of forest. The fuel reduction burning program aimed at lowering ground fuel quantities using controlled low intensity fires which did not scorch or damage the trees. Fire intensity is directly related to the quantity of fuel burnt (Byram 1959) and is a measure of the severity of a fire. Fuel reduction burning did not aim to remove all litter from the forest floor. Experience had shown that, for all but extreme weather conditions, jarrah forest fires burning in fuel quantities less than about 8 t ha^{-1} could be controlled.

In order to facilitate the large annual burning program (in excess of 200,000 ha), accurate fire behaviour guides, fuel moisture content prediction systems and fuel accumulation guides were necessary. Without such systems, there would be gross inefficiencies in planning and conducting fuel reduction programmes. Weather and fuel conditions are critical for successful fuel reduction burning. If conditions are too cool and damp, the result is a patchy, poorly burnt area. If it is too warm and dry, the result may be excessive removal of the litter layer (down to mineral earth), excessive scorch to the overstorey and damage to tree boles, or fire escapes.

In the late 1950s and early 1960s, McArthur (1959) conducted fire behaviour studies in jarrah forest near Dwellingup. The aim of his research was to predict the behaviour of fire (i.e. forward rate of spread, flame height, rate of area development and intensity) in predominantly leaf litter fuels, so that fuel reduction burning could be planned and well executed (see Chapter 3).

McArthur (1959, 1962) burnt 15 small forest plots (< 0.5 ha) under carefully monitored fuel and weather conditions. By observing and measuring fire behaviour, he developed the first jarrah forest fire behaviour prediction system. From a series of graphs, fire rate of spread, flame height and scorch height could be determined for varying weather conditions, fuel moisture and fuel quantity. McArthur's (1959) jarrah forest experiments were conducted under mild weather conditions over a four day period in autumn.

McArthur's (1959) methods were similar to those he used in fire behaviour studies in the eastern states. The forward rate of fire spread and the position of the fire perimeter was marked and weather conditions were monitored during the fires. McArthur recognized the limitation of the results of his experiments in terms of attempting to predict fire behaviour for the range of fuel and weather conditions likely to be experienced in the northern jarrah forest. He extrapolated his findings to cover a much wider range of conditions, based on his experiments in similar fuels conducted in the eastern states. While he felt that his extrapolations were serviceable, he recommended further experimentation to validate fire behaviour predictions. McArthur's early work provided the first quantifiable relationships between the way jarrah forest fires burn and fuel, weather and topography conditions. He also demonstrated a technique for conducting fire behaviour experiments. This technique was subsequently emulated by Peet (1965) and other fire researchers in Western Australia.

Peet (1965) set about improving the existing northern jarrah forest fire danger rating system originally developed by Wallace (1936), with refinements added by Stoate and Harding (1940) and Hatch (1969). Peet developed a fire danger rating system which was far more quantitative and meaningful than the previous index. Peet's system attempted to predict the forward rate of spread of a headfire, given estimates of fuel moisture (from temperature and relative humidity), fuel quantity and wind speed. He also provided guide-lines for executing fuel reduction burns. Peet's (1965) fire danger rating system and controlled burning guides for the northern jarrah forest were refined over the next 15 years.

The intended purpose of Peet's guides was to facilitate the safe and efficient operation of fuel reduction burning. This was defined by Peet (1972) as "fire which is applied to the forest at an intensity which minimises damage to the environment and to the trees". Thus, the guides were vital for planning low intensity fuel reduction burns and for planning wildfire suppression strategies.

Even given improved forest fire behaviour guides, the task of burning large areas of forest in a fuel reduction program was daunting. Fuel reduction burning from aircraft was first tested in Western Australia in 1965 (Packham and Peet 1967). Dropping incendiaries into the forest from aircraft enabled thousands of hectares of forest to be lit virtually simultaneously under carefully defined fuel and weather conditions. Aircraft could be used to achieve a broad area fuel reduction program, at a relatively low cost (see Bradbury 1981). For example, in 1984, the average cost of using aircraft to burn some 213,000 ha of hardwood forest was around 20 cents ha^{-1}. While fuel reduction is an important part of wildfire prevention, the need to have well equipped, well prepared and well trained fire fighters has always been recognized (Underwood and Christensen 1981, Underwood *et al.* 1985). There have also been significant developments in communications, aerial fire detection, equipment and suppression strategies during the last 30 years. All of these factors have been co-ordinated to provide a high level of wildfire protection to forest and human values.

3.5 Current forest management objectives

Since the late 1970s, there has been growing public and political interest in the way in which forests are managed. There have been greater community demands placed on the forest, not only for timber, but for a range of other values including conservation, scientific research, recreation and water production.

The jarrah forest is unique, containing some of the most beautiful timber, flora and fauna in the world. Apart from its uniqueness, its close proximity to a major centre of population (Perth) has created some major areas of controversy and conflict with respect to land use priorities and management strategies (Havel 1989). This created a significant re-alignment of forest management in the 1970s. There was a thorough reappraisal of the Forests Department's policies and management strategies, which included plans for the conservation of forest flora and fauna. The specific provisions for the jarrah forest were detailed in the General Working Plan for State Forests in Western Australia (Forests Department of Western Australia 1977). The essence of these changes was that the forest would be zoned into areas, so called Management Priority Areas (MPA's), which would be described according to their dominant use, and for which secondary uses would be specified. The delineation of MPA's was based on the assessment of potential demands, biophysical elements, legislative and economic constraints, and the evaluation of land use conflicts (Havel 1989).

Political, organisational and policy changes led to modifications to forest management, including fire management, which generated a correspondingly complex research program. Fire regimes were to be developed which were appropriate to the priority land use. Examples of special fire regimes to promote desired ecological responses include habitat management and disease control and these have been further described in the introduction to this thesis.

The primary legislation governing rural and forest fires in Western Australia is the Bushfires Act of 1954 which has periodically been amended, most recently in 1981. The Bushfires Act contains a number of important provisions which influence the management of fire in forest lands including:

- declaration of periods when burning is restricted or prohibited;
- daily forecasting of fire danger;
- fire break construction requirements;
- fire prevention measures relating to camp fires, sawmills and operation of machinery in the forest.

Additional legislation relating specifically to fire in State forests which was contained in the Forest Act (1918) has recently been incorporated into the Conservation and Land Management Act (1984). Relevant provisions of this legislation include:

- penalties for unlawfully lighting fires and failing to notify a forest officer of intent to burn on any land contiguous to a State Forest or timber reserve;
- protection of sawmills;
- responsibilities of licensees and permit holders;
- forest officers requesting assistance to suppress fires burning on State forest or timber reserve.

The existence and enforcement of strong legislation has been an important cornerstone in the development of fire management in the jarrah forest. The Department of Conservation and Land Management is represented on the Bushfires Board and has a policy of closely adhering to the provisions of the Bushfires Act, as did the previous Forests Department.

Fire management objectives for the northern jarrah forest are outlined in the management plans prepared for the Northern and Central Forest Regions of CALM (CALM 1985, CALM 1987 a,b,c). Separate management plans have been prepared for each of the three Forest Regions, to replace the General Working Plan (No. 87 of 1982) of the Forests Department, but each has adopted the same fire protection objectives.

The primary objectives are (from CALM Policy Statement 19, 1987):

1) To protect community and environmental values from damage or destruction by wildfire.
2) To use fire as a management tool to achieve land management objectives in accordance with designated land use priorities.

In order to meet these objectives, CALM has specific policies on fire suppression, fire use, liaison, public awareness and research which form the basis for planning and implementing fire management operations. Whatever the specified management objectives for a forest, appropriate fire management objectives and strategies must be determined. Sneeuwjagt (1989) has prepared a flowchart of the fire management planning process used in Western Australia. A firm understanding of fire behaviour, fire impact and fire effects are fundamental requirements for sound forest fire management.

CHAPTER 4

AN OVERVIEW OF APPLIED FOREST FIRE BEHAVIOUR MODELS

4.1 Introduction

The purpose of this chapter is to briefly review applied forest fire behaviour models to highlight the contribution of this research to fire science and to identify inadequacies of existing models for application to modern jarrah forest fire management. North American fire models are briefly discussed, but the main emphasis is on Australian forest fire behaviour models.

There are three main applications for which fire behaviour models have been developed. Firstly, to measure seasonal and daily fire danger, as defined by Luke and McArthur (1978). Generally, this is a numerical index, ranking fire danger from conditions when fires cannot spread, to conditions when fires will burn uncontrollably and cause destruction. The index values are often interpreted as a descriptive measure of fire danger in terms of damage potential and suppression difficulty, such as LOW or EXTREME. As such, a high degree of accuracy is not needed. Daily fire danger rating is commonly used to issue warnings to the public and to set states of readiness of fire management authorities. The second application is to predict rates of wildfire spread. This is valuable for planning and wildfire pre-suppression and suppression activities (Cheney 1968, Luke and McArthur 1978 and Beck 1988). In this application, predictions of fire behaviour need to be more precise and more accurate than those required for determining a fire danger rating index. The third application is for prescribed burning operations, where managers deliberately set fire under carefully defined fuel, weather and fire behaviour conditions to achieve specific objectives. Common examples of this are fuel reduction burns, slash burns following logging operations and burns to eradicate or regenerate specific plants.

Fire behaviour models need to be accurate and reliable when used for setting prescribed burns. For example, conducting tops disposal burns beneath fire sensitive radiata pine (*Pinus radiata*) stands can only be safely conducted over a very narrow range of weather and fuel conditions (Woodman and Rawson 1982, Burrows *et al.* 1989). Slight inaccuracies in forecasting fire behaviour could result in damage to crop trees or worse. The onus is on managers to control fires deliberately set, to within defined fire behaviour limits. Fire authorities will quickly lose credibility if prescribed fires escape to become damaging wildfires.

Fire behaviour modelling has been approached basically in three ways (Van Wagner 1985, Catchpole and de Mestre 1986 and Weber 1991):

i) Theoretically or physically based (see review by Weber 1991);

ii) Laboratory (or semi-physically) based (e.g., Rothermel 1972);

iii) Empirically (or statistically) based (e.g., McArthur 1966, Sneeuwjagt and Peet 1985, Stocks *et al.* 1987).

The various approaches to deriving fire behaviour prediction models have benefits and limitations and have been compared and discussed by others (e.g., Fons 1946, Van Wagner 1968a, 1975, 1985, Catchpole and de Mestre 1986, Beer 1991a, Weber 1991). Most authors agree that greater control of variables is possible in laboratory studies, but field experiments have a basis in reality so are more likely to reproduce the actual process of fire spread by integrating complex phenomena and numerous, difficult to measure, variables. Theoretical models should eventually result in fire behaviour laws with universal application, whereas empirically derived models should only be expected to be reliable over the same range of conditions as those under which the experiments were conducted. Statistical analysis possible with empirical data should provide a measure of variability of dependent variables for given sets of independent variables. Such confidence intervals are useful to managers. Empirically derived models are useful for specific management prescribed burns whereas theoretical and laboratory models, being universal, are likely to be unreliable when high levels of resolution are required and generally require validation. There are significant practical limitations on field experimentation to derive empirical models such as;

i) physical and economical limits to plot size and numbers,

ii) costs, risks and difficulties of implementing and containing experimental fires, especially under adverse weather conditions,

iii) legal restrictions on days when experimental fires can be lit, further limiting the range of experimental conditions,

iv) physical damage to other forest values,

v) practical limits on the quantity of data collected, therefore on the amount of detail. This is not such a problem today, but in the early 1960s when many field experiments were conducted in Australia, computing technology was limited,

vi) scaling problems associated with fire acceleration and build-up, spotting and crown fire development which are a feature of large fires.

Of the three modelling approaches, only laboratory (or semi-empirically) and wholly empirically derived models are used in fire management in North America and Australia. Models with widespread use are:

i) The Rothermel model, used in the United States (Rothermel 1972 and Andrews 1986).

ii) The Canadian Forest Fire Behaviour Prediction System (CFFBP) (Stocks *et al.* 1987, Forestry Canada Fire Danger Group 1992).

iii) The McArthur meter, used in the eastern states of Australia (McArthur 1966, 1967a and 1973)

iv) The Forest Fire Behaviour Tables for Western Australia (FFBT) (Harris 1968, Beggs 1972, Sneeuwjagt and Peet 1976, 1979, 1985).

This is despite the extensive literature on theoretical attempts to describe fire spread. Before examining the applied models, it is useful to briefly discuss theoretical modelling approaches to understand why this approach has not yet led to an ability to predict bushfire behaviour.

4.2 Theoretical models

A review of the substantial literature dealing with theoretical and mathematical aspects of fire spread will not be attempted. This subject has recently been reviewed by Weber (1991) and discussed by others (e.g. Phung and Willoughby 1965, Emmons 1965, De Ris 1969, Steward 1974, Albini 1985, Catchpole and de Mestre 1986, Nelson and Adkins 1987, de Mestr *et al.* 1989, Baines 1990, Carrier *et al.* 1991, Beer 1991, and Pitts 1991).

Even though the general mechanisms of combustion and fire spread are understood, it has not been possible to develop accurate, applied models based on first principles. Nelson and Adkins (1987) reported; "After 40 years of work by many investigators, a mathematically simple procedure for correlating and predicting the spread of wildland fires still does not exist". Similar statements have been made by Van Wagner (1985), Catchpole and de Mestre (1986), Baines (1990), Carrier *et al.* (1991), Beer (1991a and 1991b) and Pitts (1991).

Theoretically based models attempt to explain fire spread by developing mathematical solutions for complex, fundamental principles of the physics and chemistry of combustion and heat transfer. Of the nine types of physical models reviewed by Catchpole and de Mestre (1986) and the thirteen types reviewed by Weber (1991), nearly all attribute radiation as the principal heat transfer mechanism, probably because this is the easiest to conceptualise and to deal with physically. Some of the models incorporate other forms of heat transfer (convection and conduction) but without a sound basis for determining when and how these forms of heat transfer are invoked (as noted by Baines 1990 and Weber 1991). Even if physicists are eventually able to unravel this confusion and are able to predict the spread of fire under controlled laboratory conditions, applying such models to the real world of temporal and spatial heterogeniety is going to be extremely challenging. An important, tangible benefit provided by this approach is that it may offer physical explanations for statistical relationships developed from empirically based studies.

4.3 The Rothermel model

The laboratory developed Rothermel model (Rothermel 1972) is the basis for fire behaviour prediction in the United States (Deeming *et al.* 1977 and Rothermel 1983). The model is based on the principle of the conservation of energy first espoused in the context of fire behaviour by Fons (1946). Different approaches to this basic principle were subsequently investigated by other theoretical modelers (e.g., Thomas 1963, Emmons 1963, Rothermel and Anderson 1966, Anderson 1969, Berlad 1970 and Rothermel 1971). Frandsen (1971) eventually provided the basic equation form used by Rothermel (1972), while Wilson (1990) has reformulated Rothermel's equations based on additional data.

Frandsen's (1971) equation proposes that fire rate of spread in a homogeneous fuel bed is a function of the ratio of the heat flux received from the combustion source and the heat required for ignition of the potential fuel. Although radiation is assumed to be the primary source of heat transfer, heat flux terms are used for which the mechanisms of heat transfer are not known.

Working on this principle, Rothermel (1972) defined the heat required for ignition as being dependent on fuel ignition temperature, moisture content and the amount of fuel involved in the ignition process. The amount of fuel involved is a function of fuel bed bulk density and the surface area-to-volume ratio of fuel particles. Heat transfer to the potential fuel is represented by the propagating flux. This is composed of a horizontal flux and a vertical flux, representing the total heat transfer by any mechanism, encompassing radiation, convection and conduction. No attempt is made to describe the physical processes of heat transfer or to determine the relative importance of each mechanism at a fundamental level. The rate of heat release per unit surface area of the fire front (reaction intensity), is the source of, and is proportional to, the propagating flux (zero wind situation). Reaction intensity is a function of the heat content of the fuel, moisture content, mineral content, particle size, and fuel bed bulk density.

Rothermel (1972) incorporates the effects of wind and slope into the spread equation by multiplicative correction factors (wind and slope coefficients) which operate on the no wind - no slope propagating flux. The model uses an average wind speed at the poorly defined "mid-flame height". Flame height is a model output, so a conceptual enigma arises in that in order to predict flame height, hence mid-flame height, one must input a wind speed value first. Apart from difficulties with determining the "mid-flame height", there are real practical difficulties in actually determining wind speed at that height. In the U.S., the standard wind speed is measured at 20 feet above the vegetation. To determine wind speed at "mid-flame height", 20 foot wind speeds are adjusted according to a logarithmic wind profile equation first presented by Sutton (1953) and refined for fire behaviour purposes by Albini and Baughman (1979). The latter authors make a number of important assumptions in developing wind speed adjustment factors. These include;

i) the acceptance of Sutton's (1953) wind profile function,

ii) the terrain is flat,

ii) there is "adequate fetch" to establish a uniform friction layer,

iii) the wind field is a "well behaved", steady windfield which does not fluctuate significantly in speed or direction,

iv) various assumptions about flame height extension above the surface vegetation,

v) there is no interaction between the wind field and the fire.

Almost all these assumptions would be violated in a forest wildfire situation.

The Rothermel model was developed from laboratory fires in simple homogeneous fuel types (e.g., pine needles, wood cribs and wood shavings). Although natural fuels are a complex of various particle types and sizes at different orientations, thirteen fuel models have been developed to represent most of the natural surface fuels encounted in the U.S. (Albini 1976a and Rothermel 1983). Each model is characterised by a set of numerical data describing the physical and chemical parameters needed as input to the fire behaviour model. In situations where the fuel bed consists of more than one type of fuel, weighting factors, based on the contribution to the total area of fuel present by each fuel size and class category, are used to derive input values which are assumed to represent the entire fuel complex (Albini 1976b).

The Rothermel model is used for the U.S. National Fire Danger Rating System and Fire Behaviour Prediction System (Deeming *et al.* 1977). The next phase of model development is to improve the model equations and to tailor inputs and outputs to suit the expanded range of fire management needs (Rothermel 1987, Rothermel and Andrews 1987 and Andrews 1991).

4.4 The Canadian Forest Fire Behaviour Prediction System

Research and development of systems for rating forest fire danger in Canada have been ongoing since the 1920s. An overview of activity leading to the current system is given by Van Wagner (1987 and 1988), Stocks *et al.* (1989), McAlpine *et al.* (1990), Stocks *et al.* (1991), and in a recently published report by the Forestry Canada Fire Danger Group (1992).

The Canadian Forest Fire Prediction System (CFFBPS) and Forest Fire Danger Rating System

(CFFDRS) have developed along similar lines to Australian fire danger rating and prediction systems (see below). Numerous experimental fires were set in a range of fuel types and fire behaviour, weather, fuel and topographical variables measured and analysed. Well documented wildfires and prescribed fires added to the data base while laboratory studies in moisture physics and heat transfer theory complemented modelling of field data (Forestry Canada Fire Danger Group Report 1992). The Canadian system has evolved nationally and systematically, unlike the Australian situation where a variety of fire behaviour prediction systems and burning guides have originated independently to cater for individual State and agency needs.

The use and application of the Canadian system is described in detail elsewhere (e.g. Alexander *et al.* 1984, Stocks *et al* 1987, Stocks *et al.* 1989 and Canadian Forest Fire Danger Group 1992) so will be discussed only briefly here. It consists of four modules; the Forest Fire Weather Index (FWI) System, the FBP System, Forest Fire Occurrence Prediction System (FOP) (being developed) and the Accessory Fuel Moisture System (being developed) (Stocks *et al.* 1989). The FWI System determines numerical ratings (indices) of fuel moisture content for various fuel categories based on weather inputs. Together with wind speed, a rate of spread index (initial spread index - ISI) is calculated. Actual rate of spread (of surface and crown fires) and other fire behaviour variables are then estimated for specific fuel types based on experimentally derived regressions between ISI and rate of spread in that fuel type. The 16 fuel types are described qualitatively rather than quantitatively and fuel characteristics within each type are assumed to be uniform. Rate of spread is adjusted according to the Build-up Index, which reflects the available fuel quantity, and for slope.

The Canadian system is not based on functional relationships between dependent fire behaviour variables (e.g., rate of spread and flame dimensions) and discrete independent variables (e.g., fuel moisture content, wind speed and fuel structural properties). Instead it is based on regressions between observed behaviour and various indices which integrate and reflect variation in independent variables.

4.5 Australian Forest Fire Behaviour models

The first Australian attempt at a formal, somewhat scientific approach to rating forest fire danger was made by the Western Australian Forests Department (Wallace 1936, Foley 1947). Wooden cylinders or "hazard rods" were used to provide an empirical measure of fire danger, as defined by Luke and McArthur (1978). The moisture content of the rods provided a measure of fire hazard which was calibrated against a perceived degree of fire danger. The estimated fire danger was "based on the intensity, spread and damage which it is considered would be caused by fire burning in two year old jarrah leaf litter during the worst period of the day" (Wallace and Gloe 1938). Soon after, similar fire danger rating systems were developed throughout Australia (Cromer 1946, Foley 1947).

Australian bushfire research has continued on an empirical basis (e.g. McCaw 1991a). The wide diversity of Australian climates and vegetation types and the different needs of managers and State based fire control and land management organisations have so far precluded the development of a national fire behaviour system suitable for all purposes of fire management. The many fire behaviour guides in existence today attempt to either rate fire danger or predict fire spread for a range of fuel and weather conditions, or both. The guides are mostly in the form of tables, meters or nomograms and relate various descriptions of fire behaviour with selected fuel, weather and topographical parameters. In most cases, the guides have been developed by observing, measuring or experimenting with fire in the field.

Peet (1965, 1972) contended that the theoretical and laboratory procedures of Fons (1946) and others were unrealistic to attempt in Western Australia at the time. Fons' list of fuel variables affecting fire behaviour included film conductance, heat transfer factor for radiation, ignition temperature, particle spacing, surface area-to-volume ratio of fuel particles, specific heat, bulk density and temperature. In reviewing Fons' experimental procedures prior to commencing his own studies, Peet (1972) concluded that the special instrumentation and other facilities, such as a wind tunnel, necessary to conduct laboratory experiments were not available in Western Australia, and were not likely to be. Peet (1972) believed that the variables posed by Fons' theoretical model were far too difficult to measure in the field and would not win acceptance among field practitioners. It was probably for similar reasons that McArthur (1959) had earlier decided against the theoretical and laboratory techniques being pursued in the United States. Instead, McArthur, and later Peet, decided to select so called "indirect variables" (Davis *et al.* 1959) for measurement under field conditions. These variables were readily identified as affecting fire behaviour and could be relatively easily measured in the field. They included weather (temperature, relative humidity, wind speed and rainfall), fuel factors (fuel load, fuel type, fuel moisture), and topography (slope). McArthur and Peet wanted to develop practical, applied fire danger and behaviour prediction systems, consistent with the forest fire management goals of the day.

4.5.1 The McArthur forest fire behaviour meter

In the late 1950s and early 1960s, McArthur conducted more than 800 experimental fires over a range of eucalypt fuel types (McArthur 1959, 1962, 1967a). These fires were ignited from a point source and allowed to run for 15-60 minutes, during which time factors affecting fire behaviour were studied in "fair detail" (McArthur 1967a). Cheney (1968) described the fuels at experimental sites as: "Characteristic of a commercial dry sclerophyll eucalypt forest of mixed species with a fuel quantity of 5 tons per acre. The fuel consists predominantly of leaf, twig and bark litter with a smaller percentage of grass and low shrubs. The forest characteristics are as found in a commercial dry sclerophyll eucalypt forest; the dominant height is 80 feet (26 m) or more and it is well stocked. The topography is flat or gently undulating". Data from these experimental fires, together with some opportunistic observations of wildfires, were integrated to produce forest fire danger tables, and later, meters. The Forest Fire Danger Meter Mark 5 (McArthur 1973) integrates the combined effects of short and long term fuel dryness and wind velocity to produce a basic index, which is further modified by the inclusion of fuel quantity and slope. As other authors (Noble *et al.* 1980, Beer 1987, Beck 1988) have noted, the meters were constructed without functional relationships between variables and without any statistical analysis. Later, Noble *et al.* (1980) fitted equations to the relationships shown on the meters using meter values and not raw data.

McArthur chose rate of spread, flame height and spotting distance as the most useful descriptions of fire behaviour for fire control purposes. He then identified fuel moisture, wind velocity, fuel quantity and slope as the main factors determining rate of spread (McArthur 1967a). Fuel size and arrangement were recognized as being important, but no data were presented linking these variables to rate of spread. Likewise, atmospheric stability and spotting were thought to influence fire behaviour, but the complexities of these phenomena precluded attempts to implicate them in fire rate of spread. McArthur (1967a) provided empirical estimates of likely spotting distance and crown fire development.

The experimental method employed by McArthur, as described in a report on experiments conducted in forests near Dwellingup (McArthur 1959), was to mark the fire perimeter at two minute intervals and then survey the markers. This enabled linear and area spread rates to be calculated. During each fire, wind speed was measured by a sensitive cup anemometer at about 1.5 m (5 feet) in the forest. Notes were made of flame dimensions, smoke colour and other fire behaviour such as spotting and crowning.

Fuel quantity (of the litter bed) and fuel moisture content (of surface or "fresh" litter) were measured before ignition. Data were analysed by plotting each fire's maximum rate of spread against wind velocity (presumably the mean over the duration), fuel moisture content and slope factors. The technology of the day limited data analysis techniques. The resulting graphs were then reproduced on a circular Forest Fire Danger Meter used to forecast fire danger and predict real time fire behaviour (McArthur 1967a, 1973). Fuel dryness, derived from temperature and relative humidity, and wind velocity are used to determine the basic fire danger index. This is then corrected using fuel quantity and slope data to predict rate of spread. McArthur (1967a) conceded that more precise tables should be used for predicting the rate of spread of prescribed fires.

McArthur's work made an outstanding contribution to understanding bushfire behaviour and to fire management in Australia. However, there is very little scientific documentation or data published in support of the relationships he derived. His benchmark publications "Fire Behaviour in Eucalypt Forests" (McArthur 1968) and "Bushfires in Australia" (Luke and McArthur 1978) do not contain detailed descriptions of the methodology employed in developing fire behaviour relationships nor are any data or statistical analyses presented.

4.5.2 The Forest Fire Behaviour Tables for Western Australia

Peet's (1972) fire behaviour experiments in the 1960s, in the northern jarrah forest near Dwellingup in Western Australia, were the basis for the current jarrah forest fire behaviour model (Sneeuwjagt and Peet 1979). The 1985 edition of Forest Fire Behaviour Tables for Western Australia (FFBT) incorporates some of the findings from studies reported in this thesis.

Peet (1972) recognized that the fire danger rating system first developed by Wallace (1936) was no longer adequate for the changing fire management needs of the then Forests Department, which required a more accurate and effective system of predicting fire danger and fire behaviour (as described in Chapters 1 and 2 above). There had also been dramatic improvements in fire suppression equipment and strategies since World War II. In the period 1961-1965, Peet, with assistance and advice from McArthur, conducted a series of fire behaviour experiments in mature stands of upland jarrah forest near Dwellingup. The purpose of this research was to develop a practical fire danger rating system and a means of accurately predicting fire behaviour to facilitate broad acre fuel reduction burning under mild weather conditions. After an extensive literature review, Peet decided to adopt the experimental techniques of McArthur (1959). Details of these studies are presented by Peet (1965, 1967b, 1971 and 1972).

From the outset, Peet aimed to produce fire danger rating and prescribed burning guides specific to the fire management objectives of the day and specific to a defined vegetation structure and landform type in the jarrah forest (Peet 1965). This choice of vegetation/fuel type was influenced by its commercial timber value and its extent and range. Having selected the basic landform units in which to conduct the studies, Peet then set about describing and measuring understorey vegetation in considerable detail, including quantity, species present, cover and a measure of understorey flammability. Using these criteria, he further stratified his experimental sites. Details of scrub flammability ratings are provided by McCormick (1966).

Peet measured quantity, depth and type of leaf litter fuels, recognising variations in fuel bed density. He also decided to make two measures of litter bed moisture content; to measure surface litter moisture (top 10 mm) and the entire litter profile moisture. The moisture gradient within a litter bed had been recognized as being important in influencing the quantity of litter fuel available for burning and hence fire spread rate (Gisborne 1928, McArthur 1962 and Ashcroft 1967). Peet studied the moisture regime of litter profiles, and especially drying rates after rain, in an attempt to develop a fuel moisture content prediction system.

As with McArthur's experiments, Peet's fires were ignited from a point source and the fire perimeters were tagged at regular intervals for about 30 minutes after ignition. In all, 130 experimental fires were set. Headfire rate of spread was averaged over four minute intervals and ranged from about 10 m h^{-1} to 112 m h^{-1} with most fires spreading at about 30 - 40 m h^{-1} (Peet 1972). Fuel moisture content ranged from 5% to 50% of oven dry weight, with most fires burning in fuels wetter than 8%.

An on-site weather station set about 50 m from the experimental site provided regular measurements of wind speed and direction (at 1.2 m or 4 feet), temperature and relative humidity. Both surface and profile litter fuel moisture content measurements were made before and during the experimental fires. The quantity of surface litter fuel up to 0.5 inch (12.5 mm) diameter was sampled in front of the headfire.

Peet analysed his data using a simple graphical technique. Modern computer analytical techniques were not readily available at the time. He stratified the fires and then plotted rates of spread against variables such as wind speed, fuel moisture and fuel quantity, with other variables being held "constant" by the stratification procedure. Graphs were then hand fitted to the scatterplots and equations developed for the graphs. Wind velocity was found to be the most important variable affecting rate of spread, with profile moisture content and litter quantity contributing very little. A power function was used to describe the relationship between rate of spread and wind speed. Rate of spread and litter quantity were related by a linear function on the basis of previous work by Fons (1946) and McArthur (1962), even though a close examination of Peet's field data shows little relationship between the two variables. To improve this relationship, Peet reverted to burning different quantities of litter in small trays under low wind (< 1 km h^{-1}) and zero slope conditions. Even then, Peet reported that litter weight accounted for only 9.5% of the variation in rate of spread. However, moisture content was not controlled and varied from 3% to 15% in the tray experiments.

Peet (1972) identified three main factors in the jarrah forest fire danger equation. These were wind velocity, fine fuel moisture content and fuel quantity. Direct field measures of fuel moisture content were not practical inputs to a daily fire danger rating system so McArthur integrated temperature and relative humidity to reflect fine fuel moisture content (McArthur 1967a). Initially, Peet chose instead to use the measure of "fire hazard" that already existed in Western Australia (Wallace 1936, Hatch 1969) based on the moisture content of hazard rods as explained earlier. Peet (1972) calibrated the moisture content of hazard rods against that of surface litter and related the two variables by a linear equation. Thus, on rain free days, the moisture content of surface litter in the jarrah forest could be reliably estimated from hazard rods. However, a better relationships between surface fuel moisture, temperature and relative humidity was derived from fine fuel moisture experiments (Peet 1972) and was used in preference to hazard rods in the first edition of Forest Fire Behaviour Tables For Western Australia (Harris 1968). The Basic Fire Hazard (BFH) was determined from temperature and relative humidity for rain free periods. This was used with wind speed to determine the rate of spread index (ROSI) which is equivalent to the rate of spread of fire burning in standard jarrah fuel (SJF) (litter 7.6 to 8.5 t ha^{-1}) on level terrain (similar in concept to the Canadian ISI).

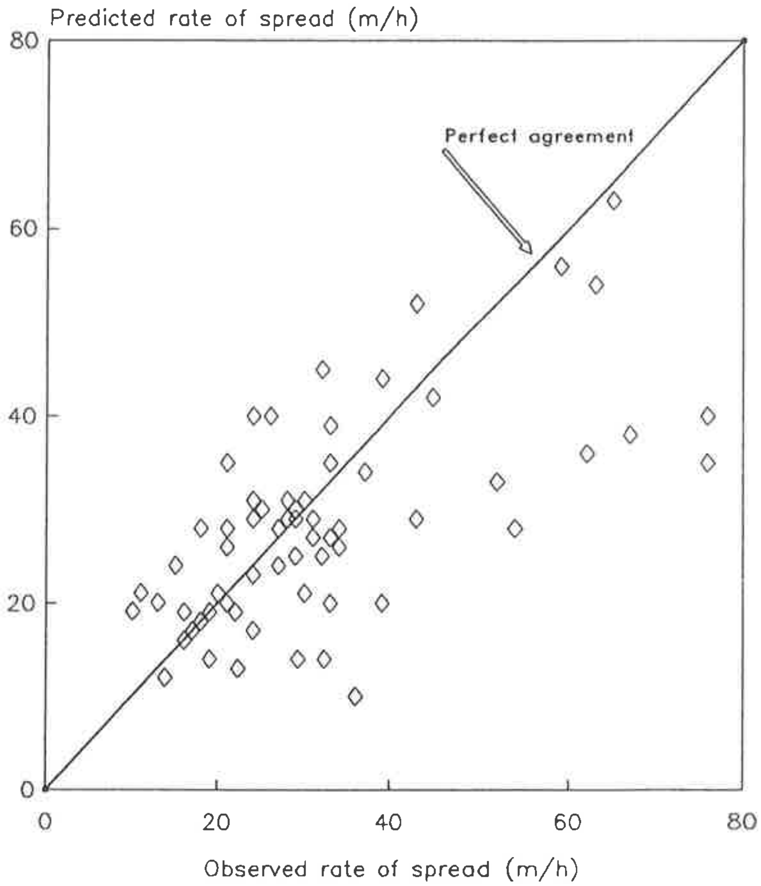
Peet recognised that the moisture content of surface fuels was not entirely adequate for determining fire hazard in deep fuels. He recognized that it was also necessary to adjust hazard according to fuel profile moisture content. Further studies were conducted to develop a profile moisture content prediction system which made allowances for rainfall. As a result, the BFH could be corrected according to amount of rain, average temperature and the number of days since rain (conceptually similar to the Canadian BUI). From his experimental fire data, Peet developed regressions relating fire spread rate and BFH and fire spread rate and wind speed for a range of fuel quantities. He then calculated correction factors to the BFH based on these equations. By applying corrections for rainfall, wind speed and fuel quantity and slope (McArthur's (1967a) slope correction factors were used), a forward rate of spread could be calculated for specific types of jarrah forest fuels. The first published version of the Forest Fire Behaviour Tables for Jarrah Forest (Peet 1965) were very similar in concept and in parameters used, to McArthur's wheel-type meters. Limited fuel accumulation data for both jarrah and karri

(*Eucalyptus diversicolor*) litter (Hatch 1955, Hatch 1964, Loneragan 1961) were incorporated into the FFBT (Harris 1968) together with guides for suppressing wildfires and conducting fuel reduction burns.

Peet tested the predictions of his jarrah fire danger rating system against 67 low intensity experimental fires in the field and found that, while the relationship between actual and predicted spread rate was poor ($R^2 = 0.59$), it was adequate for implementing low intensity, slow spreading fuel reduction burns. Peet's observed verses predicted rate of spread data have been extracted from his graph (Graph 19 page 136, Peet 1972) and are reproduced in Figure 4-1 below.

Peet (1972) cautioned that considerable errors could result when predicting high rates of spread due to extrapolation of relationships developed from slow spreading experimental fires. He reported that the actual rate of spread of several wildfires was 2 to 4 times greater than predicted by his model (Peet 1972). He was also aware that in many cases, the small, point ignition experimental fires used to develop the prediction system had not reached a steady rate of spread and were in the build-up or acceleration phase.

Figure 4-1: Fire rate of spread predicted by Peet's (1972) jarrah forest fire behaviour model with observed rates of spread. (Source: Peet 1972).



As fire control and prescribed burning operations expanded into different forest types, fire managers and researchers recognized that predictions based on studies conducted in the northern jarrah forest, were unlikely to apply to other forests, especially to the tall, wet sclerophyll karri forests of the south-west. In response to management needs, intensive fire behaviour research was carried out in the karri and southern jarrah forests near Manjimup in the early 1970s. These studies concentrated on describing the fuel structure and weights. Unlike the northern upland jarrah forest, karri and southern jarrah forests are characterised by a tall, dense understorey and often deep litter and trash (suspended, dead vegetation), representing a complex fuel. Sneeuwjagt (1971, 1973) described six structural types within the southern forests and presented techniques for measuring scrub/fuel structure and quantity. In conjunction with these studies, Sneeuwjagt (pers. comm.) carried out several hundred small (<0.5 ha) experimental fires in the field. Most of the fires were conducted under relatively mild conditions for safety reasons. Data from these fires were combined with reliable wildfire data to produce a karri rate of spread index, which was determined from wind speed and surface fuel moisture content (Sneeuwjagt and Peet 1979).

Sneeuwjagt (pers. comm.) conducted detailed studies of moisture regimes in deep karri litter fuels and successfully developed an improved procedure for forecasting fuel moisture for surface and profile litter. The procedure is detailed in Sneeuwjagt and Peet (1979 and 1985). In a recent study of moisture regimes in young even-aged karri stands, McCaw (1988) reported that the fuel moisture content predictions made for these fuels by the FFBT were reasonably accurate when run over a three month period. However, Hatton and Viney (1991) found that the moisture content prediction system did not work well outside the area for which it was developed. Surface fuel and profile fuel moisture contents are used to determine the quantity of fuel available for burning. In later editions of the FFBT surface fuel moisture content (SMC) replaced the BFH for determining the karri and jarrah ROSI. SMC could be measured in the field or predicted from temperature, relative humidity and rainfall (Sneeuwjagt and Peet 1979, 1985). Qualitative descriptions of Fire Danger Rating were based on the jarrah ROSI.

4.6 Concluding discussion

Fire management needs in Western Australia have changed and broadened in scope over the last two decades. This has necessitated an active forest fire research program to continually keep abreast of changes and to update the FFBT. Today, prescribed fire is used to achieve a range of management objectives, including fuel reduction, regeneration of and eradication of specific plant species, as outlined in the introduction to this thesis. Generally, prescribed fires to regenerate vegetation must be set under dry soil and fuel conditions in summer or autumn to achieve best results. Examples include, karri and wandoo (*Eucalyptus wandoo*) regeneration burns (Underwood *et* al. 1983, Burrows *et al.* 1991), burns to regenerate *Melaleuca viminea* and *Gastrolobium bilobum* thickets which are important habitat for the rare and endangered Tammar wallaby (*Macropus eugenii*) (Christensen 1982 and 1991), and burns to promote desirable understorey species, such as native legumes (e.g. *Acacia pulchella*), and high intensity fires to reduce the abundance of bull banksia (*Banksia grandis*) (Burrows 1985) to assist with the control of the pathogenic root fungus *Phytophthora cinnamomi* (Shea *et al.* 1976 and Shea and Malajczuk 1977).

When deliberately setting fires under the warm, dry summer or autumn conditions required for regeneration burns, accurate and dependable fire behaviour models are critical. Inaccuracies or uncertainties can result in misjudging fire behaviour, leading to intense, uncontrollable wildfires. Fire behaviour is sensitive to slight changes in wind speed and topography when fuels are dry (<8% of oven dry weight). Therefore, it is necessary to continually validate and refine the jarrah forest fire behaviour tables, which were originally developed from field experiments to provide a means of rating fire danger and for planning and implementing low intensity fuel reduction burns.

Modern fire managers use fire to achieve ecological objectives as well as to protect human life and property so fire models must be able to forecast fire danger, predict fire behaviour over a wide range of potential burning conditions and predict the physical impacts of fire which give rise to ecological effects. Theoretical modelling approaches are unlikely to result in a reliable fire behaviour prediction system which has universal application, both in terms of the variety of fire management needs and in terms of the variety of fuels, weather and topography. The main benefit of theoretical investigations is that they should lead to a better understanding of combustion and fire spread which will greatly assist with the design, implementation and interpretation of field experiments. Field based statistical or empirically derived models are reliable for the conditions under which they were developed and provide the only real option for predicting the actual behaviour of bushfires in the foreseeable future. The needs of fire and land management agencies has and will continue to change, necessitating continued experimentation, expansion and field validation of statistically derived fire models.

Eucalypt forest fire behaviour models developed by McArthur and Peet in the 1960s were adequate for the management needs of the day, but are less than adequate for today's needs. The main limitations of these models are:

i) They were developed from small, low intensity, developing fires lit over a narrow range of potential burning conditions. Extrapolation of these models beyond the experimental conditions has resulted in significant errors in predicting fire rate of spread.

ii) Many of the relationships are not functionally based but are inferred from observed correlations between variables. For example, the relationship between rate of spread and fuel moisture content presented in the FFBT was derived from an observed correlation between rate of spread and fire hazard (the moisture content of hazard rods). Fire hazard was in turn found to be correlated with temperature and relative humidity. Temperature and relative humidity were found to be related to fuel moisture content in the absence of rain. Fuel moisture content was then substituted for temperature and relative humidity without actual relationships being developed between rate of spread and fuel moisture content.

iii) The models have a poor statistical basis primarily because of the inherent variability of the dependent and independent variables associated with fire behaviour and the limited analytical skills and facilities available in the late 1950s and 1960s. Hand drawn curves were fitted to scatterplots and equations developed for the curves. No analysis of variance was carried out.

iv) Some incorrect assumptions may have been made. For example, the direct relationship between rate of spread and fuel quantity is without scientific or statistical basis and the relationship between rate of spread and fuel moisture content has been inferred from the relationship between rate of spread and fire hazard.

v) Existing eucalypt forest fire models were designed to predict fire behaviour over a narrow range of conditions and do not predict the physical impact of fire beyond estimating scorch height. Modern fire management places considerable emphasis on wildfire control and on the preservation and enhancement of conservation values.

An important contribution of this thesis to the science and management of fire is that it addresses the above limitations by experimental research. It contributes to a better understanding of eucalypt forest fire behaviour and impacts which give rise to important ecological effects over a wide range of fuel and meteorological conditions by developing functional relationships incorporating rigourous statistical analyses. The applied models that have been developed and reported in later chapters mean that jarrah forest fire managers will be able to make more accurate and precise predictions of fire behaviour and fire impact within known confidence limits over a wide range of potential burning conditions.

CHAPTER 5

FUEL CHARACTERISTICS

5.1 Introduction

Fuel is live and dead vegetation which burns in a bushfire. Its quantity and structure significantly influences the total amount and rate of energy release. With weather and topography, this will determine fire behaviour, severity of the fire in terms of suppression difficulty, and its physical impact on the forest. Therefore, detailed information about fuel composition, quantity, rate of accumulation and structure is important for understanding and modelling the ways in which fuel effects the behaviour, impact and ecological effects of bushfires. Where the appropriate models are available, fire managers need to be able to appraise fuel characteristics at any time to make estimates of wildfire behaviour and potential impact. Such information is also necessary for planning and implementing prescribed burns for fuel reduction, habitat regeneration, plant eradication or plant regeneration. Appropriate application and interpretation of the fire models reported in this thesis requires that the fuel for which the models are developed is clearly described.

The effects of fuel quantity, structure (surface area-to-volume ratio, density, packing ratio, etc.), and fuel chemical properties on fire behaviour has been reported in a plethora of fire science literature and reviewed in detail in major texts such as Davis *et al.* (1959), Brown and Davis (1973), Luke and McArthur (1978), Gill *et al.* (1981), Chandler *et al.* (1983), and Pyne (1984). McCaw (1991b) reviewed fuel measurement techniques and found that the selection of characteristics for measurement was, to a large extent, dictated by the requirements of the various fire behaviour models. The litter fuel in eucalypt forests has traditionally been described in terms of oven dry weight per unit area because this is directly related to fire rate of spread in Australian fire behaviour guides (McArthur 1962 and 1967, Peet 1965 and 1972, Luke and McArthur 1978, Sneeuwjagt and Peet 1985). These guides have been developed for specific vegetation types for which fuel physical and chemical characteristics are assumed to be constant, with the exception of fine fuel quantity and height (Cheney 1981, McCaw 1991b). Cheney (1990a) noted that there is little statistical evidence of a direct correlation between fuel quantity and rate of spread in eucalypt forest fuels, but proposed that fuel quantity may be correlated with structural changes as fuels age and that it may be these changes rather than fuel quantity which affect rate of spread. However, there have been no detailed studies of the structure of eucalypt litter fuels and no investigations into how structure affects fire behaviour, particularly rate of spread. Past research has concentrated on post-fire biomass accumulation and on the composition and decomposition of litter in relation to nutrient cycling (e.g., see Walker 1981, Raison *et al.* 1983, Hutson and Veitch 1985 and O'Connell 1991).

Hatch (1955 and 1964) and Peet (1971) have investigated litter fuel accumulation in jarrah forests and found it to be a function of tree canopy cover and time since fire. Hatch (1955) did not specify the dimensions of litter particles measured during his investigation nor did he investigate the structure of the litter layer. Peet (1971) measured fuel particles up to 12.5 mm in diameter and limited his study to fuel accumulation in the first five years after fire in order to determine appropriate time intervals between fuel reduction burns. Both investigators restricted their fuel accumulation studies to high rainfall (>950 mm), high quality commercial forest. Spatial and temporal changes in the structure and composition of the jarrah litter fuel have not been studied. Given the importance to fire behaviour now ascribed to fuel properties, these limitations warrant further investigation. Consequently, this study aimed to;

- i) quantify and describe standard jarrah forest fuel (SJF) for which fire prediction models are developed in later chapters of this thesis,
- ii) describe the accumulation of fuel for the jarrah forest range,
- iii) examine and describe spatial and temporal variation in jarrah forest fuel composition and structure,
- iv) describe physical and chemical characteristics of the litter which are likely to affect its fuel properties.

5.1.1 Standard jarrah fuel (SJF)

Jarrah forest understorey vegetation (fuel) is a continuum where floristic composition and structure vary with changing climatic and edaphic factors (Havel 1975). A general physiographic and biogeographic description of the jarrah forest is presented in Chapter 2 and detailed descriptions of site-vegetation types based on floristic assemblages are given by Havel (1975). While many of Havel's (1975) vegetation types are floristically diverse, most upland jarrah types are pyro-botanically similar (i.e. have similar fuel properties) and are represented by Havel site types S, T and P. These types are collectively referred to as standard jarrah fuel (SJF) and this is the fuel type in which Peet's (1972) original fire behaviour experiments were conducted. Reasons for focussing fire studies on this fuel type were discussed in Chapter 4. The photographs (Plate 5-1 and 5-2) typifies a standard jarrah fuel (SJF).

Litter which accumulates on the forest floor is the dominant fuel and consists of a more or less continuous, thin layer of dead leaves, fine twigs, bark and floral parts cast from overstorey tree species (*Eucalyptus marginata* and *Eucalyptus calophylla*). Lower, mid-canopy species (*Banksia grandis* and *Allocasuarina fraseriana*) also contribute, but to a lesser extent. Peet (1972) defined litter fuel as consisting of particles less than 0.5 of an inch (12.5 mm) in diameter but, as determined by the experiments described in Chapter 6, particles less than 6 mm in diameter contribute most to flaming zone combustion. In the study described by this chapter, larger particles were not measured as part of the litter fuel but formed a separate fuel class.

Hatch (1964) described jarrah forest litter as consisting of a shallow but pronounced L (fresh litter) layer consisting of fresh leaves, twigs and floral parts, a deeper F (formultningsskiktet) layer of partly decomposed material and a poorly developed H (humusamneskiktet) layer of well decomposed material. Western Australian foresters often refer to the L layer as surface fuel and to the F and H layers collectively as duff fuel.

The forest floor is also littered with dead coarse woody fuels (logs and limbs) resulting from logging operations and natural processes. These large (6 mm - 300+ mm diameter) fuel particles have a limited overall effect on rate of spread but do have an important localised effect on soil heating and bole injury to trees (Chapters 11 and 12), especially under dry conditions (Burrows 1987a).

Aerated live and dead (trash) understorey scrub fuels are low (0.1-1.5 m) and sparse (<40% cover). Live vegetation greater than about 4 mm in diameter is rarely consumed even during an intense fire (Burrows and McCaw 1990). Bark on standing trees ignites under dry conditions and is often the source material for long distance spotting (McArthur 1961a). Generally, there is insufficient aerial fuel to sustain a crown fire *per se*, although flame extension through the scrub and mid-canopy levels and bark ignition on standing trees (torching) can result in total defoliation under severe weather conditions. Fuel particles which comprise SJF are classified as shown in Figure 5-1.

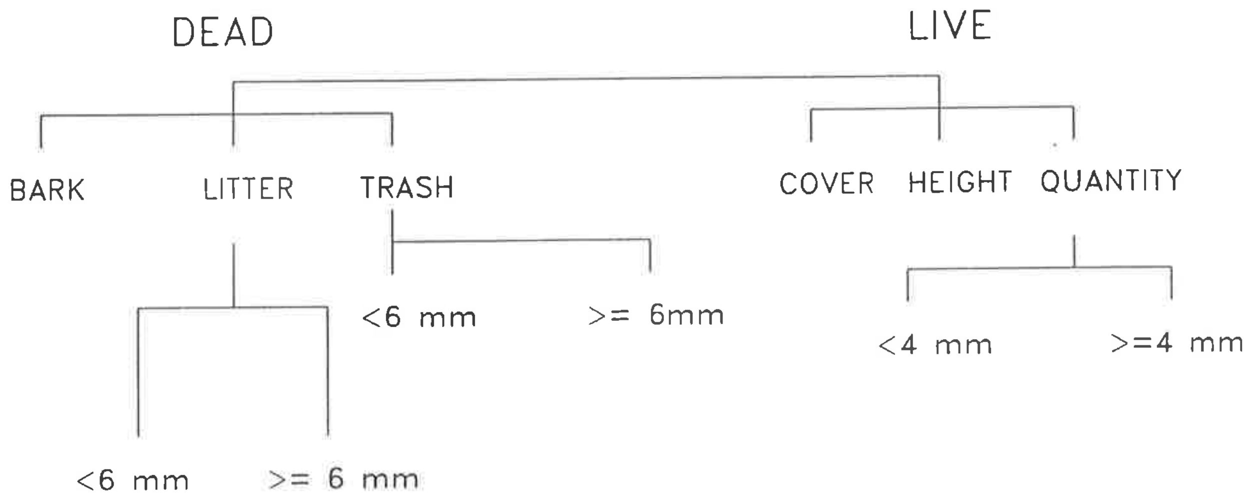
Plate 5-1: Upland jarrah forest fuel 7 years since last fire

Plate 5-2: Fifty five year old fuels in Chandler forest near Jarrahdale

Plate 5-3: Sampling surface litter fuel (< 6 mm diameter) with a 20 cm x 20 cm quadrat

Plate 5-4: Fuel particles which comprise the surface litter fuel, i.e., fresh leaves, decomposing material and twigs of various diameters

Figure 5-1: Classification of fuel elements in standard jarrah fuel array (SJF).



5.2 Methods

Upland jarrah forest fuels (SJF) of different but known age since last fire were sampled contemporaneously by firstly stratifying forests according to mean annual rainfall which affects plant growth and site productivity (Havel 1975 and Abbott *et al.* 1989) and presumably rate of fuel accumulation. Forests with a mean annual rainfall > 950 mm were classed as high rainfall forests and represent high quality commercial forests along the Darling Scarp. Forests with a mean annual rainfall of 750-800 mm were classed as low rainfall forests and represent forests along the eastern margin of the main forest belt. Sampling details are contained in Table 5-1. At each sample location, tree basal area was measured using a wedge prism (x2 factor) and tree canopy cover estimated using a periscope type-crown densiometer. Litter fuel less than 6 mm in diameter was sampled from 10 randomly located quadrats (each 0.04 m^2) located within a 20 m radius of the point from which the basal area sweep was made. The total depth of litter was measured at four locations within each quadrat then the fresh surface (L) layer was removed and the depth of the remaining fuel (duff) was measured and the material collected separately. The L layer was not a clearly defined stratum so a judgement was made on the basis of the condition and colour of the material. All material was dried, weighed and sorted as;

i) freshly fallen surface leaves (L layer)

ii) fragmented and decomposing material (duff) and

iii) twigs, bark and fruits (capsules).

Data from the 10 samples were combined to represent the sample for that location. Sampling was carried out in summer when fuels were dry (moisture content 6-10% of oven dry weight).

Combustion rate studies described in Chapter 6 revealed that fine round wood particles < 4 mm in diameter were the most flammable particles in litter fuels. The particle size composition of fine twigs in the litter is likely to significantly affect litter combustion properties. Hence it was examined in more detail to determine whether it varied with time since last fire. An additional 50 litter samples (10 x 0.04 m^{-2} per site) were taken from five forests of different, but known, ages to study temporal changes in the fractions of twigs, bark and fruits by size classes. This material was sorted into 1 mm diameter size classes, dried and weighed.

Live and dead understorey vegetation (scrub) was harvested from 5 x 1 m^2 quadrats at each sample location. The mean height of vegetation in the quadrats was estimated using a calibrated height stick. Cover was estimated visually. Harvested material was sorted as;

i) trash (dead, suspended vegetation < 6 mm diameter),

ii) live material < 4 mm diameter, and

iiii) live material >= 4 mm diameter.

All material was dried and weighed.

The quantity of downed and dead limbs and logs (>= 6 mm in diameter) on the forest floor varies considerably, depending on fire and logging history. The data presented here were collected from McCorkhill State forest, a typical commercial jarrah forest about 25 km west of Nannup. The 2,500 ha forest was sampled on a 100 m x 100 m grid, using a 20 m line transect (Van Wagner 1968b) centred on grid point.

The surface-area-to-volume ratios of the major litter fuel particles were estimated using a technique described by Brown (1970) from 30 fresh, dry leaves of each of jarrah, marri, bull banksia *(Banksia grandis)* and sheoak (*Alocasuarina fraseriana*). Fuel particle densities were determined from the same samples.

Total and silica-free mineral content of each of the litter fuel particles were determined from the above samples by John McGrath at the Department of Conservation and Land Management's soil chemistry laboratory in Perth. The procedure followed the standard technique described by the U.K. Ministry of Agriculture, Fisheries and Food (Anon. 1973).

Table 5-1: Summary of sample details of a study of fuel dynamics in standard jarrah forest fuel (SJF). There were 59 samples in high rainfall forests and 43 in low rainfall forests. The number of samples in each fuel age varied from 2 to 10 with a litter sample being the mean of 10 x 0.04 m^2 quadrat sub-samples. Mean values in parentheses.

Variable	**High rainfall (>950 mm)**	**Low rainfall (750-800 mm)**
Mean rainfall (mm $annum^{-1}$)	980-1200 (1080)	770
Time since fire (years)	1 - 52 (17)	1 - 34 (16)
Tree basal area ($m^2 ha^{-1}$)	16 - 41 (29)	11 - 35 (20)
Tree canopy cover (%)	35 - 70 (47)	20 - 50 (35)
Litter quantity (t ha^{-1})	1.5 - 24.9 (11.5)	0.8 - 18.6 (5.9)
Litter depth (mm)	4 - 42 (21)	2 - 35 (12)
Scrub quantity (t ha^{-1})	0.2 - 5.5 (2.6)	0.5 - 5.9 (2.5)
Scrub height (m)	0.1 - 1.0 (0.5)	0.1 - 1.5 (0.6)
Scrub cover (%)	5 - 30 (16)	5 - 35 (20)

Facilities such as a bomb calorimeter were not available to determine the heat of combustion of fuel particles. Calorific studies of eucalypt forest fuels in eastern Australia (e.g., Walker 1963, Pompe and Vines 1966, Specht 1969, Vines 1981, Dickinson and Kirkpatrick 1985), revealed that most fuels have values in the range 16,000-23,500 kJ kg^{-1} of dry material. This is similar to the range reported by Susott *et al.* (1975) for a variety of natural fuels in the United States. Allowing for incomplete combustion, a standard calorific value of 18,700 kJ kg^{-1} (dry) was adopted for the fuel particles studied here (after Van Wagner 1973).

5.3 Results and discussion

5.3.1 Litter fuel accumulation

Leaves, twigs and floral parts < 6 mm in diameter form the dominant fuel type in SJF, both in terms of quantity and continuity. Of the total cover of litter, about 85% was dominated by material cast from overstorey *Eucalyptus* trees with lower tree species such as bull banksia (*Banksia grandis*) and sheoak (*Alocasuarina fraseriana*) contributing the balance. Jarrah leaves rarely live longer than two years (Hatch 1955, Loneragan 1956 and 1961) and at the beginning of summer (about December) the old leaves are shed as the branchlets die (Abbott and Loneragan (1986) citing Stoate and Wallace 1938). Most litter fall in jarrah and karri (*Eucalyptus diversicolor*) forests occurs over the dry summer months (January, February and March) (Hatch 1955 and 1964). The rate and amount of litter fall in eucalypt forests is affected by seasonal conditions of rainfall and temperature (McColl 1966, Lee and Correl 1978 and Pressland 1982) and other factors such as flowering, fire and outbreaks of defoliating insects.

The dominance of the litter layer as a fuel in SJF is supported by observations of fires which are primarily carried in the litter. Under severe weather conditions, flames may be lifted into the tree canopy by heavy litter patches (such as beneath thickets of bull banksia or sheoak), by dense clumps of saplings, patches of scrub, logging debris, or bark on standing trees, resulting in localised torching and defoliation of the overstorey.

The quantity of litter on the jarrah forest floor is a function of time since last fire, canopy cover and mean annual rainfall. Spatial variation measured within a forest reflects the variability in canopy cover of overstorey and understorey trees contributing to litter fall with localised heavy accumulations beneath dense thickets of bull banksia and sheoak. For example, at a site in high rainfall forest which was burnt 8 years previously, the litter quantity beneath a dense sheoak thicket was about 24 t ha^{-1}, more than double the average loading for the forest. Fuel quantities measured beneath dense bull banksia thickets were often 50% higher than the average value for the forest block.

Mean litter quantity and variability (standard errors) are graphed with time since fire for low and high rainfall forests of different canopy cover in Figure 5-2. Litter accumulates rapidly in the first 5 years reaching a constant mean level of about 8 t ha^{-1} in low rainfall forest and about 16 t ha^{-1} in high rainfall forest by about 15 years. The latter steady state level is within the range reported for other dry sclerophyll forests (e.g., Fox *et al.* 1979 and Simmons and Adams 1986). The standard errors varied from 4% to 14% of the mean, tending to increase with increasing fuel age (Figure 5-2). There were insufficient data to analyse high rainfall forests with low canopy cover (<40%). The relationship developed by Raison *et al.* (1983) using Hatch's (1955) data for 35% canopy cover is graphed for comparison.

Jenny *et al.* (1949) first proposed that litter accumulation could be described by equations of the form;

$$W_t = S_S(1-e^{-kt}),$$

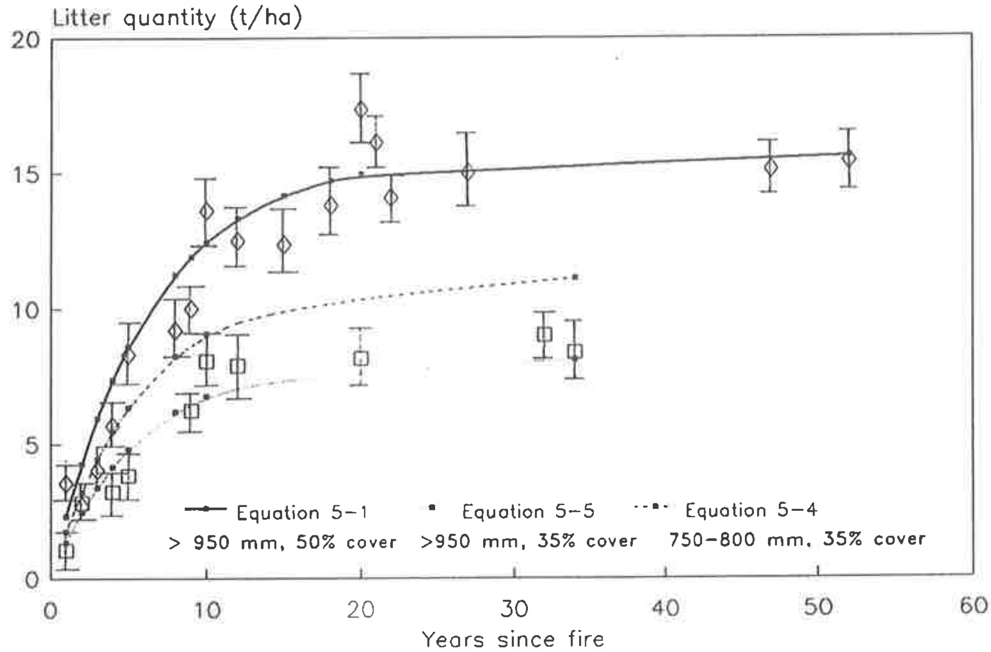
where W_t is the weight of litter accumulated at time t under steady state conditions and k is a decomposition constant. Litter accumulation has been modelled using this equation for a number of other Australian eucalypt forests (e.g., Fox *et al.* 1979, Walker (1981), Raison *et al.* 1983 and O'Connell 1987). Hatch (1964) and Peet (1971) found that an equation of the form [logW] = a+b[logt] best described the accumulation of litter in high rainfall jarrah forest. Peet (1971) found no evidence of levelling off of fuel quantity and Hatch (1964) suggested that a steady state condition would probably be achieved 40-50 years after fire. Data in Figure 5-2 show that litter accumulation reaches a plateau by about 16 years after fire. The oldest jarrah forest fuel sampled by Hatch was only 22 years old and by Peet, 5 years old, which probably explains why they estimated that litter accumulation probably continued for 40-50 years. It is also possible that Hatch's samples included larger dimension particles which would take longer to decompose.

The functionally based exponential recovery equation form proposed by Jenny *et al.* (1949) and used by Raison *et al.* (1983) best fitted the litter accumulation data gathered during this study. Parameter estimates are shown in Table 5-2 and equations for various forest types are graphed in Figure 5-2. These equations provide simple but useful means of predicting mean litter quantity for the entire range of the jarrah forest.

Table 5-2: Values of equation parameters for predicting litter fuel quantity in high and low rainfall forests and for two canopy cover classes. Standard errors are shown in parentheses. The fuel accumulation equation is of the form $W_t = S_S(1-e^{-kt})$, where W_t = litter quantity (t ha^{-1}) after time t (years), S_S = steady state quantity (t ha^{-1}) and k = decay constant.

Forest	S_s	k	Equation number
High rainfall (>980 mm annum-1)			
Canopy cover 50%	15.60	0.16	Equation 5-1
	(0.76)	(0.03)	
Raison *et al.* (1983) using Peet's (1971) data			
Canopy cover 50%	16.4	0.13	Equation 5-2
	(7.7)	(0.08)	
Raison *et al.* (1983) using Hatch's (1955) data			
Canopy cover 50%	17.7	0.11	Equation 5-3
	(1.5)	(0.04)	
Canopy cover 35%	11.1	0.17	Equation 5-4
	(0.8)	(0.04)	
Low rainfall (750-800 mm annum^{-1})			
Canopy cover 35%	8.10	0.18	Equation 5-5
	(0.66)	(0.05)	

Figure 5-2: Fine litter fuel quantity with time since last fire for for two canopy cover classes in high (>950 mm) and low (750-800 mm) rainfall jarrah forests. Equations are in Table 5-2.



Mean annual litter fall varied from about 1.3 t ha^{-1} $annum^{-1}$ for low rainfall forests to about 2.4 t ha^{-1} $annum^{-1}$ for high rainfall forest. Litter fall for high rainfall jarrah forest is similar to that reported for other Australian dry sclerophyll forests (e.g., Lee and Correll 1978, Birk and Simson 1980 and Raison *et al.* 1983) and is about one third of that reported for mature karri (*Eucalyptus diversicolor* F. Meull.) (Loneragan 1956, Peet 1971, O'Connell and Menage 1982 and O'Connell 1991) and blackbutt (*Eucalyptus pilularis*) (Birk and Bridges 1989), which are wet sclerophyll forests. The decay constants (k) shown in Table 5-2 (0.11-0.31 $year^{-1}$) are within the range reported for most other eucalypt forests (e.g., Raison *et al.* 1983, O'Connell and Menage 1982 and Hutson and Veitch 1985) but are significantly lower than that reported by Simmons and Adams (1986) for dry sclerophyll forests near Melbourne (0.44). The significant difference between the steady state litter quantity for high and low rainfall forests reflects variability associated with climatic and local site factors affecting litter production rates. The steady state litter accumulation in high rainfall forests is about double that for low rainfall forest which is lower than has been reported for any eucalypt forest.

Fuel quantity is an important consideration for planning and implementing fuel reduction burns. While it can be predicted using the equations presented in Table 5-2 above, fire managers need to confirm the actual average quantity of fuel in a forest block prior to prescribed burning. Destructive sampling is the most accurate method, but it is time consuming and costly so indirect methods such as measuring fuel depth and using pre-determined relationships with fuel quantity are often employed. A measure of fuel depth is also necessary for determining fuel structural properties such as bulk density and packing ratio. Sneeuwjagt (pers. comm.) designed a litter depth gauge for quickly and accurately measuring the depth of litter fuels in Western Australian forests and tables were constructed for estimating fuel quantity from depth (Sneeuwjagt and Peet 1985). This approach is also used in fuel types in other parts of the world (e.g., Williston 1965, Woodard and Martin 1980 and Harrington 1986). The relationship between litter depth and quantity for jarrah forests studied here is presented in Figure 5-3 together with the relationship developed by Sneeuwjagt and Peet (1985). The marked difference between the two relationships is largely due to the different techniques used to measure depth; the litter bed is slightly compressed when using the Sneeuwjagt litter gauge. The relationship between depth and quantity provided by Sneeuwjagt and Peet (1985) is valid when using the Sneeuwjagt litter depth gauge but will over-estimate the bulk density and packing ratio of the litter. The regression equation in Figure 5-3 explains most variation in litter quantity but in such shallow fuel beds, precise and accurate depth measurements are essential if repeatable predictions of fuel quantity are to be made. The values plotted in Figure 5-3 are the means of four depth measurements made in each of the 0.04 m^2 quadrats. In addition to operator error in measuring depth, particularly of light and sparse fuels less than 10 mm deep, there is natural variation in the bulk density and composition of the litter throughout the forest.

5.3.2 Litter fuel composition

The proportion of fresh surface leaves, decomposing material, and woody material varies with time since last fire as illustrated in Figure 5-4. Standard errors range from 4.5% to 22.1%, with the fraction of woody material being the most variable. Equations describing compositional changes of the litter with time since fire are summarised in Table 5-3.

In the first 2-3 years after fire the litter consists almost entirely of an L layer comprised of freshly fallen leaves, twigs and floral parts. By about 2-3 years after fire, the quantity of material in the L layer is more or less constant at about 2.5-3.5 t ha^{-1} for high rainfall forest and 1.0-2.0 t ha^{-1} for low rainfall forest. The quantity in the F and H layers (decomposing duff) steadily increases for about 15 years after fire. The quantity of twigs and fruits, although highly variable, tends to increase with time (Figure 5-4) probably because these particles are more resistant to decomposition than the finer leaves. By about 15 years, when litter accumulation has virtually stabilised, the L layer contributs about 20% to the total quantity with duff material contributing about 46% and woody twigs and fruits scattered throughout the litter bed making up the balance.

Figure 5-3: Fine litter fuel quantity on the jarrah forest floor as a function of depth of the litter bed.

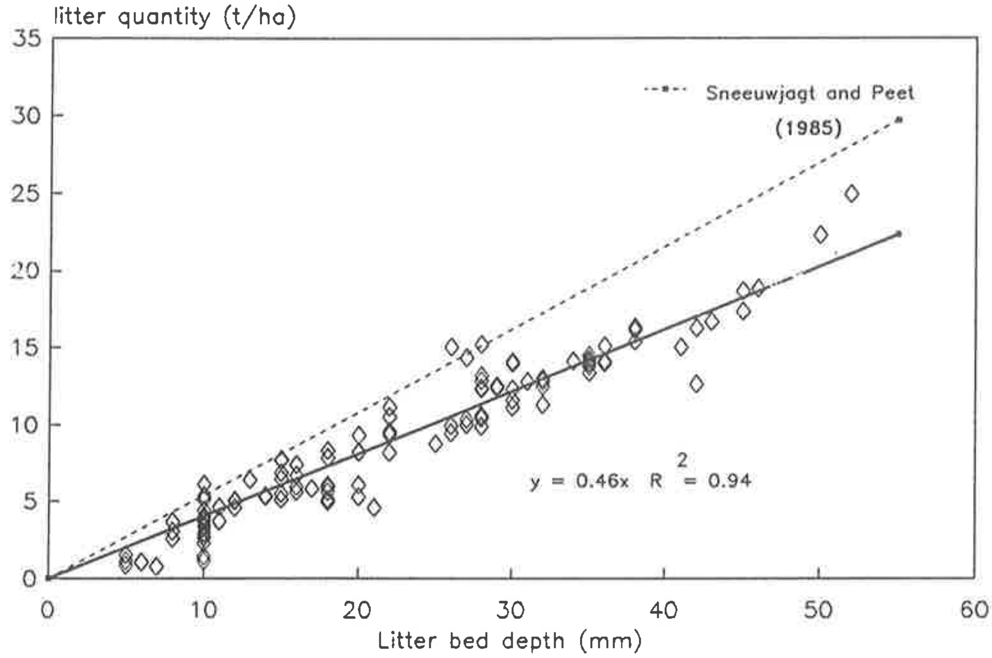


Figure 5-4: The changing composition of the jarrah forest litter layer with time since last fire. Fresh leaves (L), duff (F and H) and woody material (twigs, fruits, bark) are shown as a per cent of the total litter quantity.

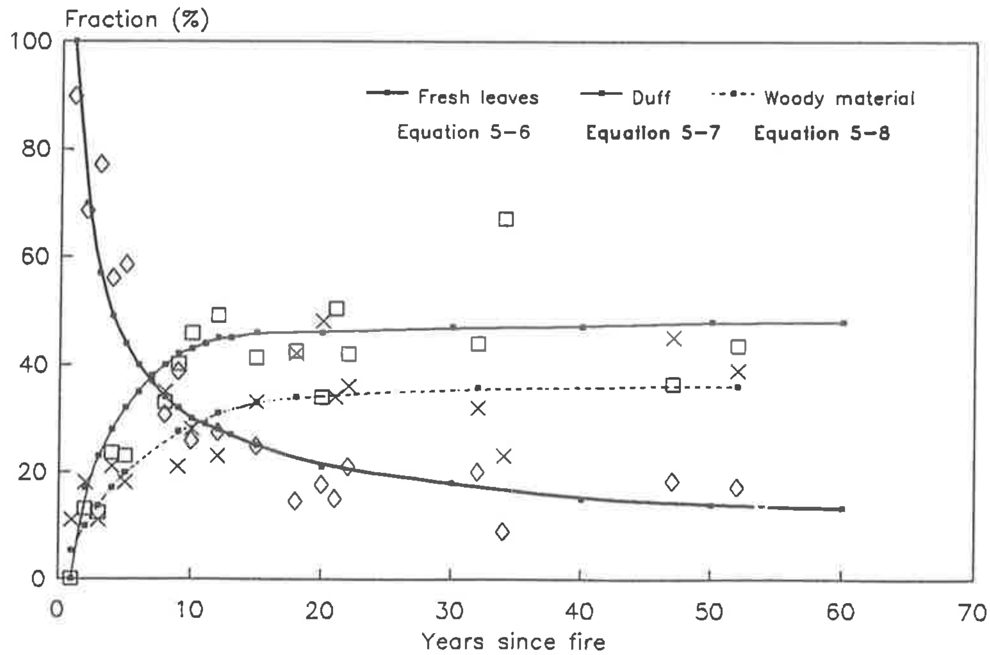


Table 5-3: Equations describing the contribution of various fuel fractions expressed as a percent of the total litter quantity with time (t years) since fire. Parameter standard errors are in parentheses. Equations are graphed in Figure 5-4.

Fuel fraction	Equation	Equation number
Fresh surface material	$S = 100t^{-0.51}$	Equation 5-6
	(L layer)	(7.9) (0.03)
Duff material	$D = 47.6(1-e^{-0.23t})$	Equation 5-7
(F and H layers)	(1.8)	(0.03)
Twigs and fruits <6mm diam.	$T = 36.2(1-e^{-0.16t})$	Equation 5-8
	(1.6)	(0.02)

The size class distribution of fine twigs, fruits and bark as a proportion of total litter quantity did not show any temporal patterns, but remained more or less constant with time. Duncan's multiple range test (SAS Institute Inc. 1985) applied to the mean fraction of each size class across five fuel ages failed to show any significant differences. The mean composition of litter by particle size classes is summarised in Table 5-4.

Table 5-4: The mean particle size class composition expressed as a percentage of the total litter quantity for litter fuels of different ages since fire. Ten samples were taken in each fuel age. Standard errors in parentheses.

Age	leaves	Duff	Bark	Round wood diameter classes (mm)					
(Years)				<1	1-2	2-3	3-4	4-6	6-10
2	68.4	0.0	3.5	3.4	7.9	12.9	1.8	2.1	0.0
	(3.7)	(1.8)	(0.6)	(1.4)	(1.5)	(1.8)	(2.1)		
6	16.8	47.2	2.2	3.2	7.9	12.2	6.7	3.7	0.0
	(2.3)	(3.4)	(1.3)	(0.5)	(1.5)	(1.3)	(2.3)	(1.1)	
12	17.5	53.6	4.7	2.6	6.4	7.5	4.1	3.3	0.0
	(1.5)	(2.9)	(1.4)	(0.4)	(1.0)	(1.2)	(1.4)	(1.1)	
16	14.0	59.0	4.5	0.6	2.7	4.4	1.5	7.9	5.0
	(1.8)	(3.9)	(1.7)	(0.3)	(0.8)	(1.2)	(0.8)	(2.3)	(1.6)
32	7.2	71.4	1.6	2.7	4.5	4.3	3.0	1.5	3.7
	(1.0)	(2.6)	(0.5)	(0.4)	(1.1)	(1.3)	(1.0)	(0.9)	(2.2)

5.3.3 Litter fuel structure

For the first two years after fire, the loosely arranged freshly fallen material forms a light and patchy ground cover (40-70%) with a low bulk density and packing ratio (Figure 5-5). By about 3-4 years the litter completely covered the forest floor and a thin duff layer had formed beneath a layer of freshly fallen material. The bulk density and packing ratio of the litter fuel stabilised at about 42 kg m^{-3} and 0.076 respectively (Figure 5-5).

After about 4 years after fire the litter fuel consists of a 10-15 mm deep surface layer of fresh, loose material (L layer) which had fallen in the last 2 years, and a lower layer of older, more compacted decomposing material which steadily increased in depth and quantity with time until about 15 years after fire. The physical structure of the two layers was significantly different with the mean bulk density of the L layer being about two thirds that of the duff layer (Table 5-5). Particle density used to calculate the packing ratio varies considerably depending on the state of decomposition of the particle. Fresh, recently fallen leaves and twigs has a mean density of 716 kg m^{-3} (S.E = 63.2) compared with 412 kg m^{-3} (S.E. = 51.6) for partially decomposed material. The mean density of all particles in a 7 year old fuel in high rainfall forest is 547 kg m^{-3} (S.E. = 53.8). Smith (1982), working in karri fuels, found a similar range in particle densities depending on the degree of decomposition and plant species. Based on these fuel particle densities the mean packing ratio of the L layer was about one third of the duff layer (Table 5-5). Hatch (1964) observed that the jarrah litter bed became stratified with age due to the more or less constant annual deposition rate and the increasing rate of decomposition, but this has not been previously quantified for eucalypt litter fuels. Barney *et al.* (1981) reported that the humus (H) layer in four Alaskan forest types had a bulk density two to three times greater than the litter (L) layer.

Table 5-5: Mean bulk densities and packing ratios for various strata of jarrah forest litter fuel from 102 samples in fuel ages ranging from 4 to 52 years since fire. Standard errors in parentheses.

	Litter stratum		
	Surface (L)	**Duff (F and H)**	**Profile**
Bulk density (kg m^{-3})	31.5* (0.97)	50.0* (1.89)	42.3 (0.074)
Packing ratio	0.038* (0.0011)	0.121* (0.0040)	0.073 (0.0013)

- Significantly different at the 0.05 level

Figure 5–5: Variation in bulk density and packing ratio of jarrah litter fuel with time since last fire.

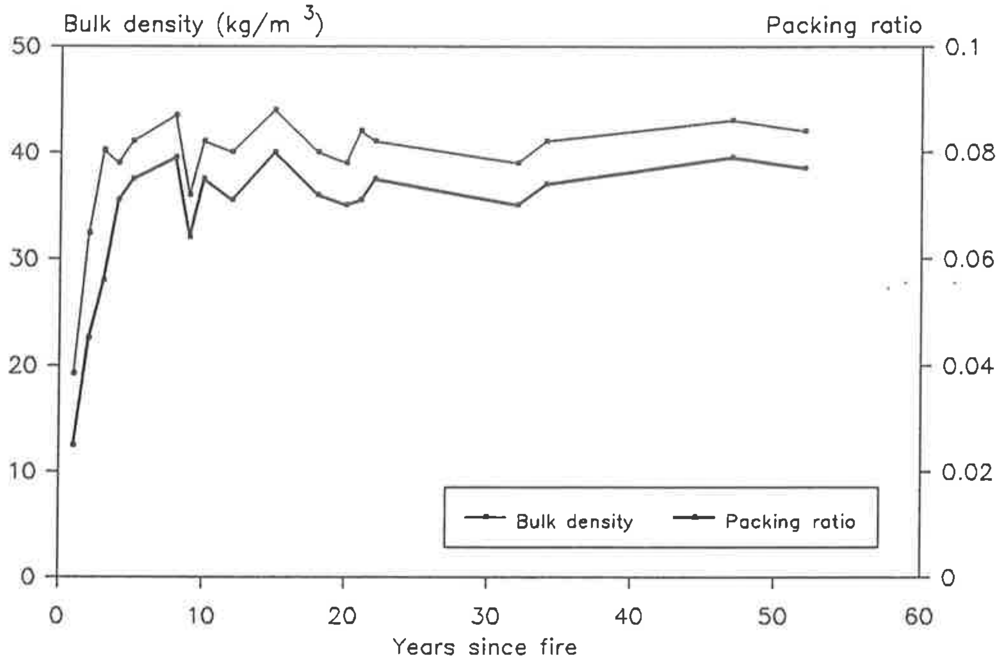
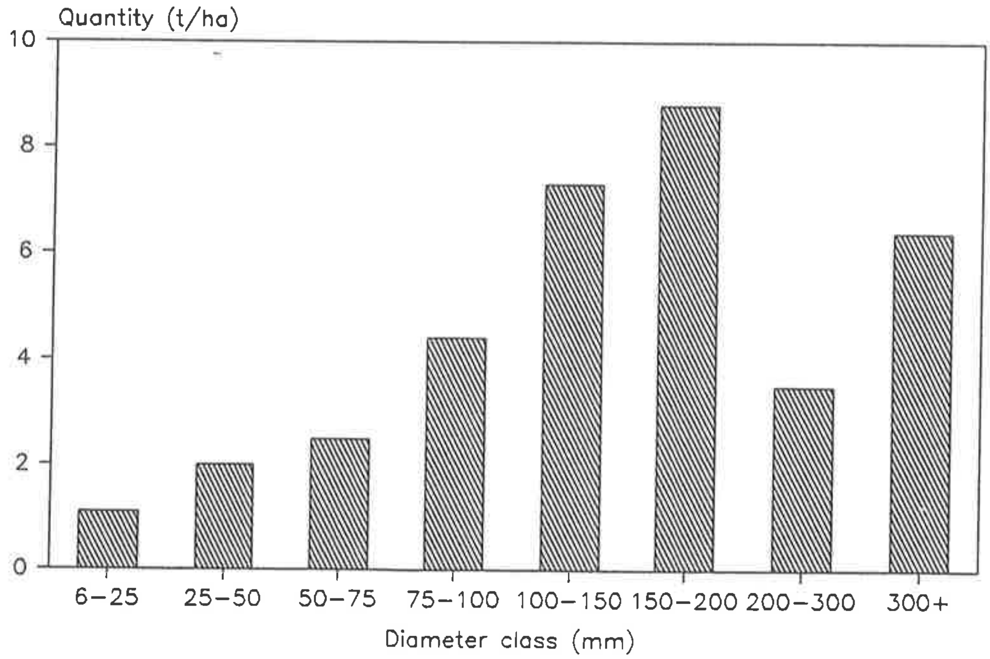


Figure 5–6: Mean quantity of coarse woody fuel on the floor of a typical jarrah forest near Nannup, W.A. last burnt 6 years previously. The quantity of coarse fuel depends on the history of logging and fire.



5.3.4 Coarse fuel quantity

The quantity of dead and downed woody material > 6 mm in diameter measured in McCorkill State forest which had been prescribed burnt by low intensity fire 7 years previously is shown by size classes in Figure 5-6. Larger diameter material is highly variable in quantity and in distribution across the forest floor reflecting past timber operations and natural processes of limb cast and tree fall.

5.3.5 Litter fuel chemical properties

Analysis of a wide range of plant material has shown that combustion properties of natural fuels are affected by the mineral content of the material (e.g., Broido and Nelson 1964, King and Vines 1969 and Philpot 1970). Philpot (1970) examined material in which the ash and silica-free ash content ranged from 0.01% to 27.07% and 0.01% to 25.27% respectively, and found that flammability decreased with increasing levels of these minerals. Mineral levels of jarrah leaves (Table 5-6) are within the normal range of natural fuels examined by Philpot (1970) who presented a table ranking 21 plant species according to increasing levels of ash and silica-free ash levels. On this basis, jarrah leaves rank 8th, having similar mineral properties as cheatgrass (*Bromus tectorum*) and ponderosa pine (*Pinus ponderosa*). Jarrah forest understorey vegetation contains a lower level of silica-free ash than jarrah leaves (Table 5-6 below).

5.3.6 Aerial scrub fuel accumulation and structure

The quantity, cover and height of understorey scrub (aerial fuel) varies considerably, depending on local site factors, such as tree canopy cover and species composition. However, most variation could be explained by time after fire (see Equation 5-9, Appendix 1). The total quantity of aerial scrub increases rapidly in the first 10 years after fire and then gradually decreases after about 20 years as short lived understorey species senesce and collapse to the forest floor. Generally, longer lived species which persisted for up to 50 years since fire developed thick woody stems and are sparsely foliaged. About 70% of jarrah forest understorey species resprout following fire (Christensen and Kimber 1975 and Bell *et al.* 1981) which probably accounts for the high initial post-fire rate of cover and biomass increase. Mean total and flammable aerial scrub fuel quantity (suspended dead material < 6 mm and live material < 4 mm in diameter) are plotted with time since fire in Figure 5-7. Standard errors ranged from 8.0% to 40.3%. Estimates of the quantity of scrub available as fuel could be made using the maxima equation below derived from data for both high and low rainfall forests.

Figure 5-7: Mean total biomass of understorey vegetation (scrub) and mean quantity available as fuel.

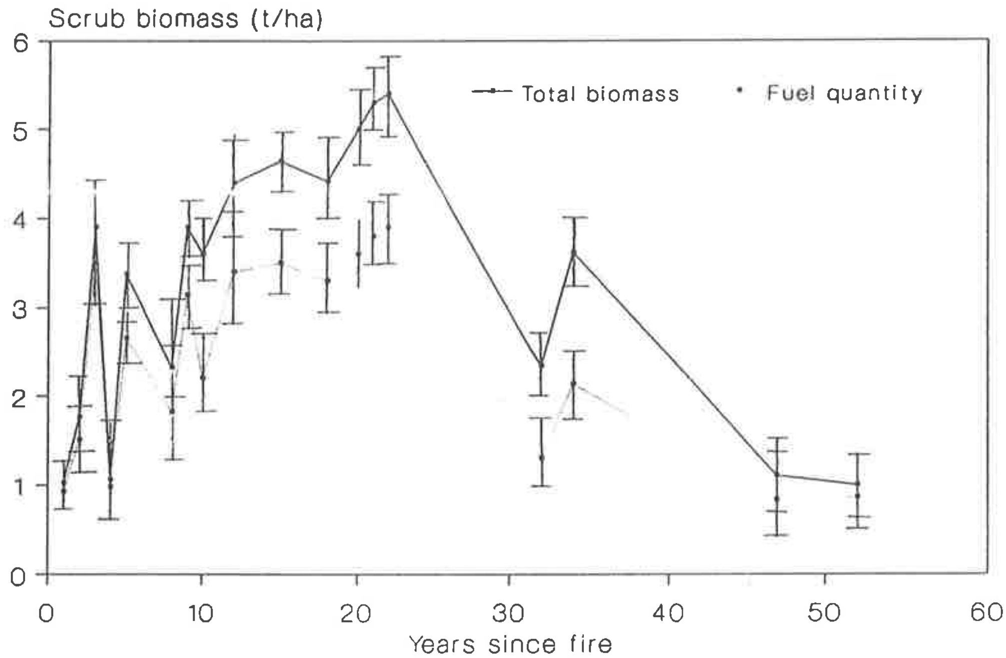
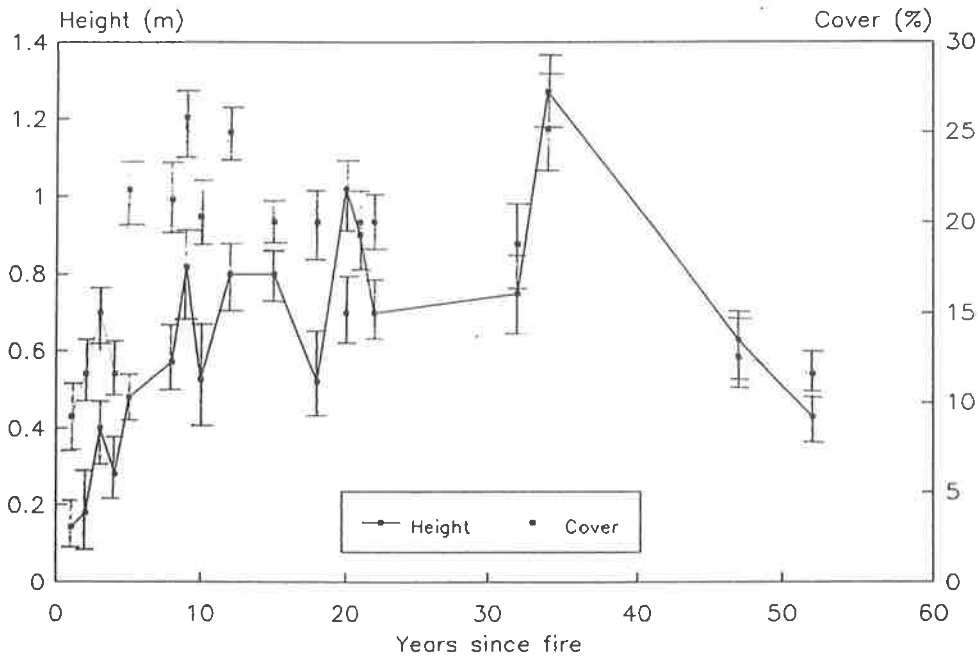


Figure 5–8: Variation in mean height and cover of scrub with time since last fire.



$F_S = 0.517t(e^{-0.072t})$ (Equation 5-10),

where F_S = available scrub fuel quantity (<4 mm diameter) (t ha^{-1}) time t years after fire.

Scrub cover and height are also variable (Figure 5-8), but increase rapidly with time after fire, stabilizing at about 10 years, then declined after about 40 years. Understorey scrub is relatively sparse and probably has a limited, localised effect on fire behaviour. In forests with a dense understorey, such as karri forests and jarrah forests on moist sites, structural changes such as senescence of the understorey are likely to result in an accumulation of dead, suspended (aerated) material which could significantly affect fire behaviour.

Plate 5-5: 10 year old jarrah fuels in a dry forest type (annual rainfall ~750 mm) east of Manjimup.

Plate 5-6: Bark on standing trees readily ignites under dry summer conditions.

5.3.7 Bark as fuel

Jarrah and marri have rough, fibrous, flaky bark which is persistent to the small branches. The dry, fibrous outer bark burns readily and contributes to the energy of the fire. Under dry conditions, bark carries fire into the tree canopy, resulting in crown scorch or defoliation. Burning pieces of bark carried aloft in the convection column can cause hop-overs and intense down-wind spot fire development which can seriously frustrate suppression activities.

As with most trees, jarrah bark thickness increases with tree size reaching a maximum of 25-35 mm at breast height (1.4 m above ground) when the tree is about 30 cm in diameter at breast height and measured over bark (dbhob) (Abbot and Loneragan 1986 and Burrows 1987a). The amount of bark which burns varies according to bark moisture content and the intensity of the fire. A high intensity wildfire near Dwellingup burnt 60% of the bark on standing jarrah trees, equivalent to 9.7 t ha^{-1} (Peet and McCormick 1965b). Ward *et al.* (1985) calculated bark loss following several moderate intensity (500-1,000 kW m^{-1}) summer fires in jarrah forest by measuring bark thickness before and after burning and the height to which stems were charred. They reported that bark thickness at 150 cm above ground was reduced by up to 10 mm and estimated that 4-6 t ha^{-1} of bark was burnt during these fires. Gill *et al.* (1986a) found that bark loss for messmate stringybark (*Eucalyptus macrorycha*), although variable, rose with increasing fuel quantity burnt and with fire intensity, plateauing at an intensity of about 1,000 kW m^{-1} when bark thickness was reduced by 8-9 mm at 55 and 120 cm above ground. Burrows (1987a) reported that moderate intensity (500-1,200 kW m^{-1}) summer fires reduced bark thickness (150 cm above ground) on large jarrah and marri trees (< 30 cm dbhob) by 7-10 mm, especially on the leeward side of the bole. Tolhurst *et al.* (1992) studying low intensity fires in mixed stringybark forests in the Australian State of Victoria, measured bark losses of up to 7 mm for small trees and 34 mm for large trees at 50 cm above ground. They estimated that 7 t ha^{-1} of bark was burnt (out of a total bark quantity of 23 t ha^{-1}).

While intense fires under dry conditions cause a reduction in bark, fire exclusion leads to an increase in bark with maximum thickness being obtained by about 19 years after low intensity fire (Abbott and Loneragan 1986). Large jarrah trees in a forest unburnt for 50 years had a mean bark thickness of 35 mm (Lachie McCaw pers. comm.) compared with 25 mm for similar size trees in regularly burnt forest (Burrows 1987a).

While bark is removed by fire, a significant amount is charred and remains on the tree. The depth of charred bark measured on large jarrah trees (at breast height) after a moderate intensity summer wildfire varied from 2-5 mm. Decortication and weathering of fire blackened (charred) bark is reported to take 15-20 years (Wallace 1965) although Abbott and Loneragan (1986) recorded small amounts of charred bark on trees last burnt 51 years previously.

5.4 Concluding discussion

The characteristics of standard jarrah forest fuel (SJF) described above are summarised in Table 5-6. The fire behaviour studies described in later chapters were carried out in this fuel type so the models developed by this research apply to this fuel. Fuel quantity (weight per unit area) is the fuel characteristic most used by Australian fire models to predict fire behaviour in particular fuel types, but quantity alone insufficiently describes the flammability and the dynamic properties of jarrah forest fuel. Accumulation and decomposition rates of litter fuel varied with forest cover and rainfall, thus changing the structure of the fuel bed. Where these factors were constant, fuel quantity, a function of time since fire, reflects structural changes. The most dynamic structural changes in the litter bed occurred in the first 4 years after fire. Thereafter, bulk density, packing ratio and the size composition of round wood, important properties which reflect the flammability of a fuel (Rothermel 1972), remained more or less constant. Fuel quantity continued to accumulate for up to 15 years after fire.

In the first two years after fire, the litter fuel is composed of freshly fallen leaves and fine twigs but with time, and up to about 15 years, the fraction of decomposing (duff) material steadily increases. These changes in fuel structure and composition may influence its burning characteristics so need to be taken into account when studying fire behaviour and fire impact. Of particular importance is the top 10-15 mm of the litter, the L layer, which consists of recently abscised, loosely arranged flammable material over older, more compacted and less flammable decomposing material. The quantity, cover and height of understorey vegetation, while highly variable, increases for up to 20 years since fire, then declines. These changes, especially the structural changes, could significantly affect fire behaviour.

The rate of fuel accumulation forms the basis for planning fuel reduction burns in jarrah forests to minimise the impact of wildfires (Peet 1971). Experience has shown that direct attack on forest headfires is unlikely to succeed when flame heights are more than 3 m or when fires are spreading faster than about 100 m h^{-1} (Underwood *et al.* 1985). Providing litter fuel quantities in jarrah forests are maintained at less than about 8 t ha^{-1} then direct attack on the flanks of a fire will generally succeed even under extreme weather conditions (Underwood *et al.* 1985). From the equations in Table 5-2, litter fuel quantity will reach 8 t ha^{-1} in 5 and 10 years for high and low rainfall jarrah forest respectively. Fuel reduction burning of 70% of the jarrah forest at 5-10 year intervals has provided a high level of community protection from the impact of severe wildfires (Underwood *et al.* 1985).

Table 5-6: Summary of mean physical and chemical properties of a six year old standard jarrah fuel. Litter profile characteristics are typical of a high rainfall mature forest with a mean canopy cover of 50%. The quantity of fuel actually consumed by fire (available fuel) will depend on fuel moisture and weather conditions.

	Fuel property							
Fuel class	W	D_F	P_d	F_d	SAV^{-1}	Ash	SFA	PR
Litter profile 6 years since last fire	8.6	21	547	41	55.1	4.57	1.33	0.074
Litter surface (L layer)	3.0	10	716	31.5	-	-	-	0.043
Coarse woody fuel on forest floor (>6 mm diameter)	41.1	>6	740	-	4/D	-	-	-
Live aerated scrub < 4 mm	1.8	360	-	0.33	153.5	3.56	0.20	-
Bark on standing trees	16 t ha^{-1} depending on fire intensity							

Where:

W = total quantity of fuel (t ha^{-1})
D_F = depth (mm) (not compressed)
P_d = particle density (k gm^{-3})
F_d = fuel bed bulk density (k gm^{-3})
SAV^{-1} = surface-area-to-volume ratio jarrah leaves (cm^{-1})
Ash = Total ash as % of total dry weight
SFA = Total silica-free ash as % of total dry weight
PR = packing ratio; P_d/F_d (after Rothermel 1972)

Describing the fuel in terms of forest type, time since last fire, quantity and depth, forest canopy cover, and rainfall, conveys more information about its properties than its age or quantity alone. The fire models developed by this research apply to standard jarrah fuel, as defined and described by this chapter. The effect of fuel quantity on fire behaviour and impact, and the combustion properties of the various fuel particles which make up the standard jarrah fuel are addressed in the following chapters.

Temporal changes in fuel structure, leading to increased fuel flammability with time after fire, are likely to be highly significant in forests which have a tall, dense understorey such as low lying jarrah forests and karri forests. This aspect, and the effects of these structural changes on fire behaviour, requires further investigation.

CHAPTER 6

COMBUSTION RATE OF LITTER FUEL PARTICLES

6.1 Introduction

The physical dimensions of fuel particles and their arrangement within a fuel bed directly affects fire behaviour. Fine fuel elements burn faster than coarse ones and there is an optimum combustion arrangement of fuel particles depending on particle size. Laboratory studies have largely examined fuel beds of homogeneous fuel elements such as excelsior, dowels or stick cribs of uniform dimensions and surface area to-volume-ratio has been used to describe the physical properties of elements regardless of their shape (e.g., Curry and Fons 1938, Gross 1962, King and Linton 1963, Rothermel and Anderson 1966, Anderson 1969, Smith and Thomas 1970, Block 1971, Rothermel 1972, Heskestad 1973, Fijioka and Fujii 1980, and Anderson 1990). Natural fuels such as jarrah litter are a heterogeneous mixture of flat and round particles of a variety of sizes (Chapter 5).

The Rothermel model (Rothermel 1972) requires specific information about fuel properties such as fuel depth, load, particle surface area-to-volume ratio, particle and fuel bed bulk density (Rothermel 1972 and Deeming *et al.* 1977). The model assumes that a single characteristic parameter can be used to represent the heterogeneous mixture of fuel particles and that this parameter can be derived by mathematical weightings based on the surface area of fuel within each size class (Rothermel 1972 and Burgan and Rothermel 1984). Fuel properties are difficult to measure in the field so for model application, fuels are classified primarily according to fuel quantity and how it is distributed among fuel particle size classes (Albini 1976, Deeming and Brown 1975 and Anderson 1982).

Australian and Canadian fire behaviour guides use fuel quantity or height to predict fire behaviour in a particular vegetation or fuel type where structure and composition are assumed to be constant (Chapter 4). The structure of jarrah forest fuel is not constant (Chapter 5), varying with time since fire, canopy cover and rainfall. However, if the vegetation or fuel type is defined in these terms, then fuel quantity correlates well to structural properties because it is correlated to time since fire (Chapter 5). Fuel particles which burn in the flaming zone of surface fires and which contribute most to fire spread and intensity have been termed fine fuels or litter fuels and consist of dead leaves, twigs, branches, floral parts and bark shed from trees and understorey vegetation. The upper size limit of fine fuels varies from 0.25 inches (6 mm) (McArthur 1962) to 0.5 inches (12.5 mm) (Peet 1972). The latest edition of "Forest Fire Behaviour Tables for Western Australia" (Sneeuwjagt and Peet 1985) sets a fine fuel (dry) limit of 10 mm diameter.

Cheney (1981) pointed out there was no clear basis for setting the upper size limit for fine fuels and suggested that the limits were selected for convenience of measurement and from visual observations of fires burning in the field. Defining an upper limit for fuel particles contributing most to heat release is meaningful for fuel beds with uniform quantities and proportions of various sizes and shapes of fuel particles but it does not specify the relative importance of the various particle classes. The mixture of fuel particles which make up a fuel bed will affect fuel bed burning properties and as reported in Chapter 5, this changes with time. Determining the contribution of the various sizes and shapes of fuel particles to flaming zone combustion and the proportion of these particles in the fuel bed is important for understanding fire spread, for calculating intensity and for interpreting fire impact.

Cheney (1991a) measured the residence time of individual fuel particles in thinning debris in young stands of *Eucalyptus seiberi* to estimate the contribution of larger pieces to the flaming zone of a wildfire. He confirmed McArthur's (1962) observations that material less than 6 mm in diameter contributes most to the heat release of a moving fire. Cheney (1991a) did not measure leaves, which make up a significant proportion of the total litter quantity in jarrah forests (Chapter 5).

This study aimed to examine the combustion properties of individual fresh dry leaves and of round wood of various dimensions which make up the jarrah forest floor fuel bed. Fuel particle flame residence time (the period of flaming combustion) and the rate of weight loss during combustion were measured to quantify and compare the flammability of the various particles. These parameters were also used to determine the relative contribution of the various particles to the combustion properties of the entire litter bed, thus providing information about how the flammability of a fuel bed might change as its composition changes. Knowledge of the combustion properties of individual fuel particles also provides a basis for setting an upper size limit for fuels involved in the flaming zone and enables the contribution of larger particles to be quantified.

6.2 Methods

Two methods were used to measure flame residence time and rate of weight loss of freshly fallen (1-3 months since abscision) leaves, dry twigs, and branches collected from the jarrah forest floor. Firstly, the flame residence time of small diameter (1-16 mm) fuel particles was determined by placing an oven dried leaf or twig (round wood) of known dimension on a metal gauze platform suspended over a pilot flame (a flaming pool of methylated spirits, see Plate 6-1). Round wood was cut into 10 cm lengths. Leaves were 80-140 mm long, 20-60 mm wide and 0.3-0.5 mm thick (mean thickness = 0.36 mm). When the particle ignited, the pilot flame was extinguished and the particle allowed to burn freely on the gauze platform. The time taken to flame-out (flame residence time) was recorded. A total of 88 pieces of round wood, 35 fresh dry leaves and 25 green leaves (moisture content 80%-120%) were tested this way.

The second method involved a load cell platform to measure rate of weight loss of larger material during combustion. Dry twigs and branches up to 80 mm in diameter were cut to a length of 300 mm and sorted into diameter size classes. Leaves and fine twigs (< 2 mm in diameter) formed a separate category.

The studies were conducted at the Manjimup fire laboratory on an aluminium table (1 m x 1 m) mounted on four insulated load cells (Plate 6-1). Signals from the load cells passed to an amplifier, to a summing module and then to a continuous ink/chart recorder. The instrumentation also provided a real time digital readout of the weight of fuel on the table to within 0.01 kg. In order to maintain similar loads on each cell and to minimise oscillations caused by drafts during the fires, the table was balanced on a central pedestal which was supported by the load cells. The weight of the fire table plus pedestal was tared off and the system tested and chart graduations calibrated using known weights. Chart speed was varied according to the size of particles on the table.

Fuel was removed from the oven and allowed to cool before being weighed and sized by measuring the diameter at the middle of each piece. The load cell equipment was not sensitive enough to accurately measure the rate of weight loss of individual leaves and fine twigs so piles of these particles were burnt instead. A known weight (about 1,000 g) of material was placed on the table. Larger pieces of round wood were loosely arranged so that burning rates would be controlled by the fuel particle thermal properties and not be influenced by surrounding particles (Anderson 1969, Anderson 1990). In relatively undisturbed forest large pieces of round wood (>6 mm) are rarely found stacked, but are scattered on or within the litter fuel.

Plate 6-1: A round wood piece burning on a gauze platform. Round twigs <6 mm diameter and leaves are the most flammable component of the jarrah forest fuel complex.

Plate 6-2: Loosely arranged fuel pieces burning on a load cell platform.

A small quantity (10-15 ml) of methylated spirits was sprayed over the dry fuel on the table using a hand mister and then lit with a fussee match resulting in instantaneous ignition of the surface of the fuel pile. All experiments were conducted in still air at ambient temperatures ranging from 26-32 ^{o}C. The weight of fuel on the table was traced continuously by the paper chart recorder as the fuel pile burnt and events such as ignition time, flame-out (cessation of flaming combustion) and burn-out (cessation of glowing combustion) were marked on the chart. When all combustion was complete (burn-out) and there was no further weight loss, the residue was weighed on a laboratory balance to verify the accuracy of the load cell system. Where necessary, the chart was then re-calibrated on the basis of the balance measurements made before and after burning.

A total of 51 fires were set on the load cell platform. The mean diameter of fuel particles was used to represent the particle size for each fire. The rate of weight loss during flaming combustion was determined from the chart traces and data were analysed using SAS (SAS Institute Inc. 1985) nonlinear and linear regression procedures.

6.3 Results

6.3.1 Flame residence time

Flame residence times for individual fuel particles (1 - 16 mm in diameter) burnt on the gauze are graphed with particle diameter in Figure 6-1 and with surface area-to-volume ratio in Figure 6-2. Round wood flame residence time increases with particle size according to Equations 6-1 and 6-2 below. Parameter standard errors are shown in parentheses and ANOVA tables are contained in Appendix 2.

$t_r = 0.871(d)^{1.875}$ (Equation 6-1),

(0.080) (0.038) (parameter standard errors)

$t_r = 880.58(S_{AV})^{-1.875}$ (Equation 6-2),

(43.67) (0.038)

where t_r = flame residence time (seconds), d = round wood diameter (1-16 mm), and S_{AV} = surface area-to-volume ratio (cm^{-1}).

Equation 6-1 is similar to that reported by Cheney (1991a) for *Eucalyptus sieberi* logs with an initial diameter up to 10 cm, and by Clements and Alkidas (1973) for white fir (*Abies concolor*). The mean residence time for individual dry leaves with a mean thickness of 0.36 mm and a surface area-to-volume ratio of 55.5 cm^{-1} is 11.73 seconds (standard error 0.058). This is equivalent to the residence time of round wood of about 4 mm in diameter (surface area-to-volume ratio of 10 cm^{-1}). The mean residence time for green leaves is 12.23 seconds (standard error 0.076) which is not significantly different to dry leaves (at the 0.05 significance level), although the green leaves took longer to ignite. Even though the flat leaves had a high surface area-to-volume ratio, they burnt slowly compared with round wood of a similar ratio. For example, using Equation 6-2, a round wood particle with the same surface area-to-volume ratio as a leaf would burn out in about 0.5 seconds which is about 23 times faster than a leaf.

The mean residence time of many pieces of similar size burning on the load cell platform is slightly longer than for individual pieces burnt over gauze. This is probably due to the different modes of ignition and the better aeration provided by the gauze platform. Residence time for round wood burning on the load cell platform is related to diameter by Equation 6-3 below and is graphed in Figure 6-3.

$t_r = 7.361(d)^{1.236}$ (Equation 6-3)
(1.92) (0.069) (parameter standard errors).

The piles of dry leaves and fine twigs (equivalent to 10 t ha^{-1}) which burnt on the load cell platform have a mean flame residence time of 32.75 seconds (standard error 1.39) which is equivalent to the residence time of an individual piece of round wood 6.8 mm in diameter (Equation 6-1). The pile of leaves and fine twigs was ignited on the surface and the fire burnt down through the pile so the residence time would be expected to increase with pile depth (or fuel quantity).

Burn-out time is defined by Cheney (1981) as the time taken for all components of the fuel complex to burn out. In this study, fuel particles of similar dimensions were burnt on the load cell platform so burn-out was defined as the period during which all combustion (flaming and glowing) takes place (after Gill and Knight 1991). This was determined from the load cell traces when there was no further weight loss. Fine fuels usually burnt completely to ash, whereas larger fuels often extinguished before all woody material had burnt. The burn-out time for 1,000 g of leaves on the 1 m^2 table (equivalent to 10 t ha^{-1}) varies from 4.2-6.8 minutes, the mean of seven test fires being 5.3 minutes. For round wood fuels deemed to have burnt completely, resulting in a residue of ash and crumbled charcoal pieces, the burn-out time varies directly with diameter as shown in Figure 6-4. Round wood 15 mm in diameter has a burnout time of 12-15 minutes whereas 65-70 mm diameter limbs have a burnout time of 120-140 minutes.

6.3.2 Rate of weight loss

The shapes of the weight loss curves for fuel particles burning on the load cell platform are similar to those reported by Armstrong and Vines (1973) and Gill *et al.* (1978). The latter authors described the curves as asymmetric sigmoid curves of the Gompertz form (after Bliss 1970). Once ignited, the material burnt at a constant rate until the flames went out and further weight loss was due to glowing or smouldering combustion. A typical rate of weight loss curve for a burning pile of fresh, dry (about 5% odw) eucalypt leaves and twigs <2 mm in diameter is shown in Figure 6-5. The constant rate of weight loss during flaming combustion and the transition from flaming combustion to glowing or smouldering combustion (flame-out) is clearly evident from the trace. Flaming combustion consumed 65-75% of the initial fuel weight with a further 20-25% being consumed by smouldering combustion.

The rate of weight loss during the flaming combustion of 1,000 g of initial fuel evenly distributed over 1 m^2 (equivalent to 10 t ha^{-1}) for all fuel particle sizes burnt on the load cell table is shown in Figure 6-6. Leaves burn slower than round wood with similar surface area (Figure 6-6). The rate of weight loss for round wood is related to particle diameter by;

$$W_L = 36.98(d)^{-0.910} \quad \text{(Equation 6-4)},$$

(4.61) (0.073) (parameter standard errors)

where W_L = rate of weight loss per 1,000 g of initial fuel (g s^{-1}) and d = particle diameter (mm).

Figure 6-1: Flame residence time for individual fuel particles burning on a gauze platform by particle diameter. The mean of 36 dry jarrah leaves is shown separately.

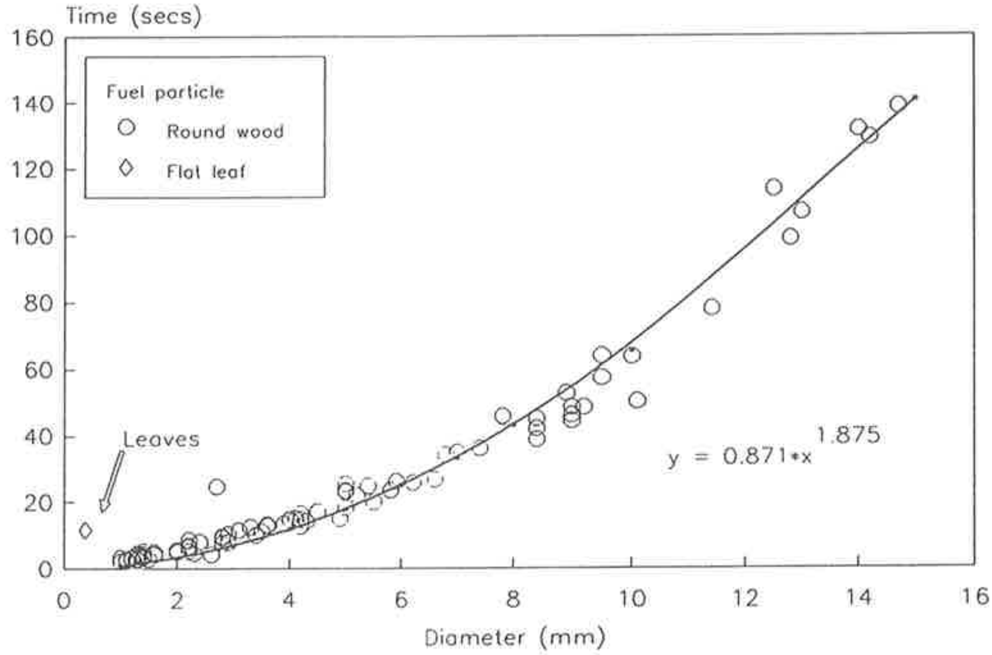


Figure 6-2: Flame residence time for individual fuel particles burning on a gauze platform with particle surface area-to-volume ratio. The mean of 36 dry jarrah leaves is also shown.

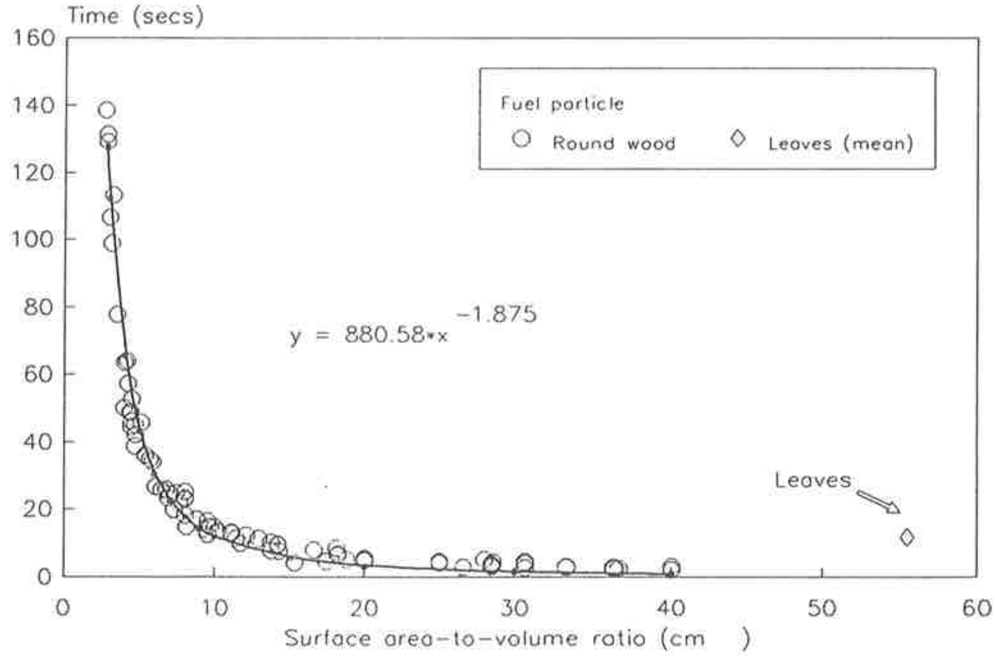


Figure 6-3: Flame residence time for single fuel pieces on gauze and for piles on a load cell platform.

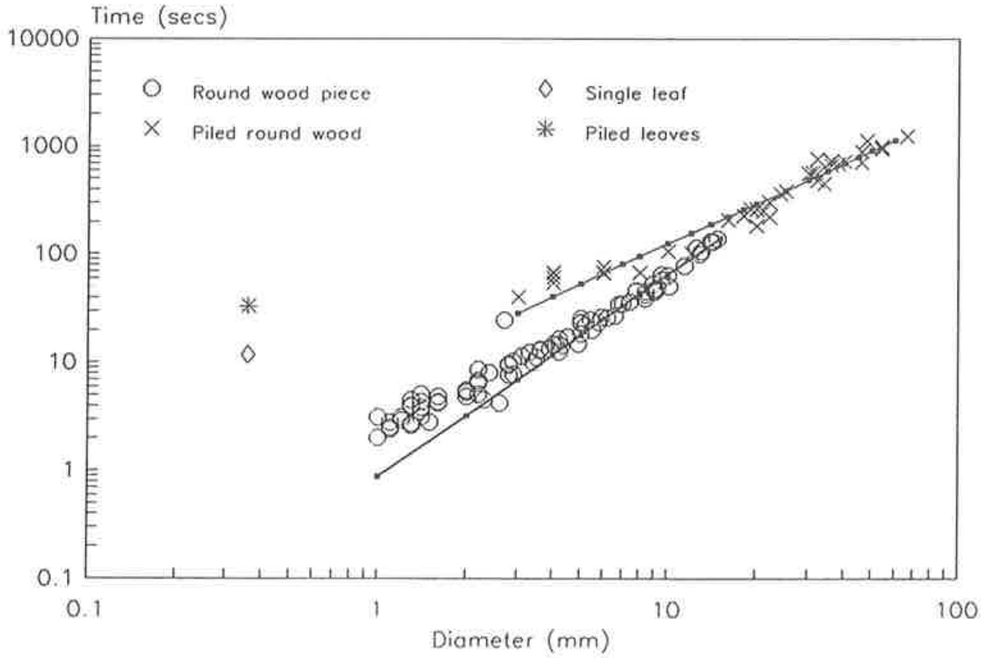


Figure 6-4: Time taken for complete combustion (burn-out) of dry round fuel particles with particle diameter.

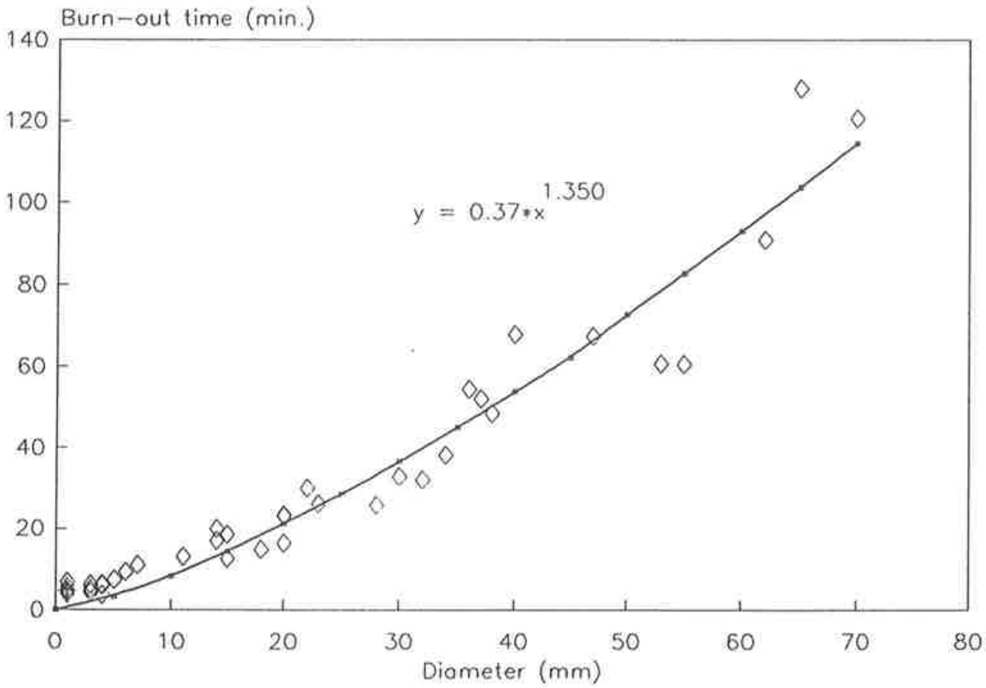
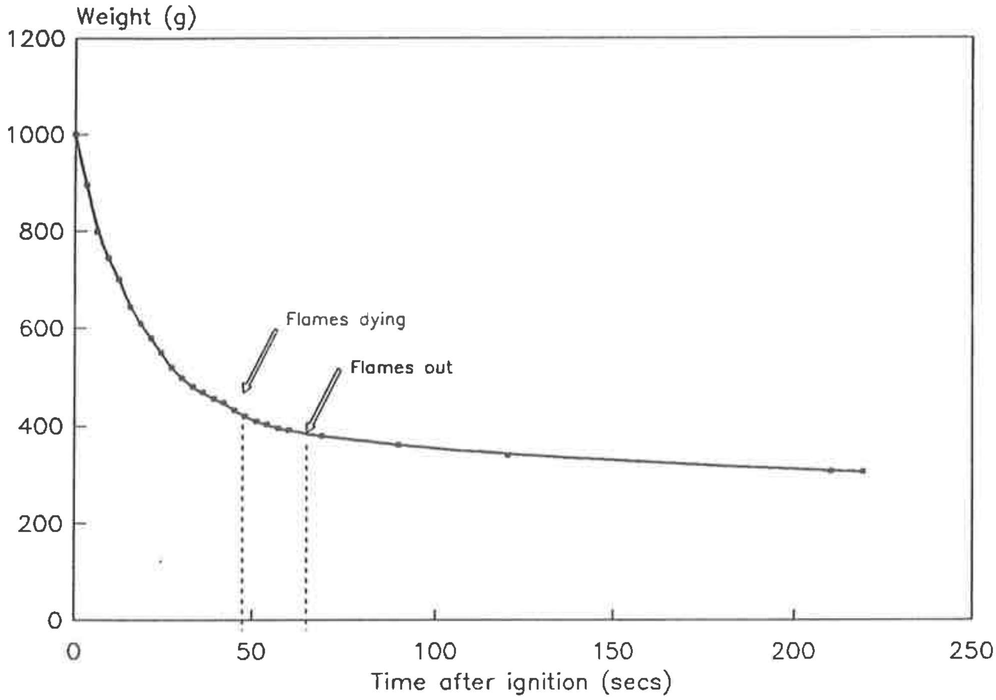


Figure 6–5: Rate of weight loss of a pile of fresh dry jarrah leaves burning on a load cell platform.



Rate of weight loss increases rapidly with decreasing round wood diameter below about 4 mm. Piles of dry leaves and fine twigs burn at a rate of 11-20 g s^{-1} with a mean of 17.1 g s^{-1} (standard error 0.21). Gill *et al.* (1978) found that the burning rate of baskets of leaves of an east coast *Eucalyptus* species was directly related to the load of leaves in the basket. They reported that a maximum basket load of 43 g had a maximum burning rate of 0.48 g s^{-1} which equates to 11.2 g s^{-1} for 1,000 g, assuming a constant relationship. This is at the lower end of the range reported here for dry jarrah leaves burnt on the load cell platform.

Large pieces of round wood rarely burnt completely during these experiments. Material larger than about 10 cm would not burn for more than 1-2 minutes so no attempt was made to burn larger pieces. The proportion of round wood burnt during flaming combustion varied from 20%-95% of the initial weight with small diameter wood usually burning more completely than large wood. The total proportion burnt by all forms of combustion varied from 25%-96%. The proportion of dry leaves burnt during flaming combustion was around 60-75% of the initial weight and the weight of ash residue was 15-20% of initial weight. The extent of combustion of large woody material during field fires is also variable, depending on fuel dryness, wind speed and the intensity of fire in the litter fuel.

The fuel fraction burnt by various phases of combustion, and the residue, is shown in Figure 6-7 for the various classes of dead fuel found on the jarrah forest floor. The data in Figure 6-7 are mean values for each fuel class. The increase in the proportion of fuel consumed by glowing combustion with increasing fuel particle size is clearly evident from these data.

Figure 6–6: Rate of weight loss of 1,000 g of initial fuel burning on a load cell platform with fuel particle size.

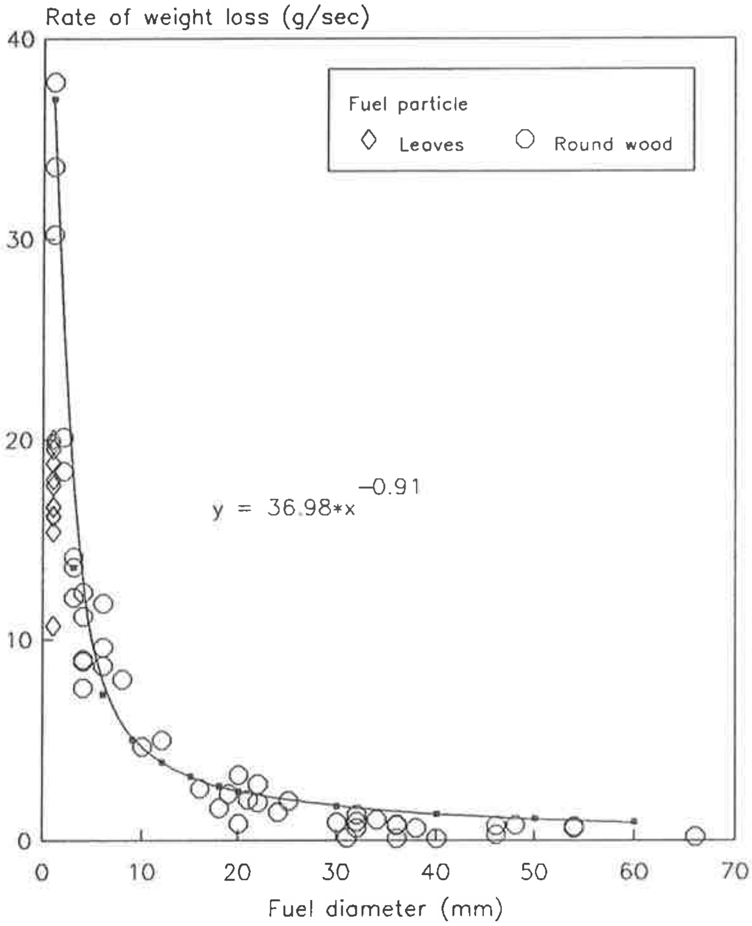
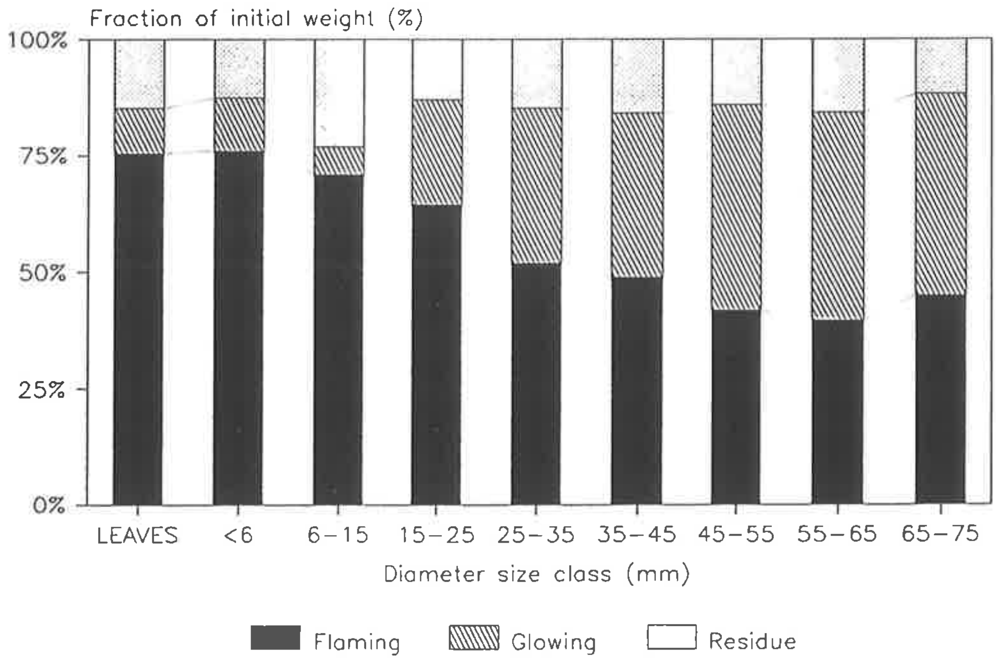


Figure 6–7: Fuel fraction burnt during various combustion phases with fuel particle size.



6.4 Discussion

Shape and physical dimensions affects the combustion properties of fuel particles. Fine round twigs < 4 mm in diameter burn very rapidly so can be considered as the most flammable elements of the jarrah litter bed. The combustion properties of leaves is similar to that of a 4 mm twig, even though the surface area-to-volume ratio of flat leaves is considerably higher. Therefore, the composition of the fuel bed in terms of the fraction of various fuel element shapes and size classes affects the combustion properties of the bed. The composition of jarrah litter changes in the first 10 years after fire; the fractions of fine twigs and of duff steadily increases, and the fraction of fresh leaves decreases (Chapter 5 above). By about 15 years after fire, the composition of the litter remains more or less constant. Based on the combustion studies of individual fuel particles (Figures 6-1, 6-2 and 6-5), this could be interpreted as the litter bed becoming increasingly flammable in the first 15 years after fire, then stabilizing. The quantity of each of the fuel fractions making up the litter mainly depends on time since last fire, canopy cover and site productivity (correlated with rainfall) (Chapter 5), so fuel quantity alone is not sufficient to describe the combustion properties of eucalypt forest litter fuel.

All fuel particles which burn contribute energy to flaming zone combustion, although the level of contribution, or the relative importance of the various fuel particles to flaming zone fire behaviour varies from substantial, in the case of fast burning fine twigs and leaves, to little, in the case of large, slow burning round wood. The average flame residence time for piles of leaves and fine twigs (equivalent to 10 t ha^{-1}) burning on the load cell platform (stationary fires) is 33 seconds or about 0.55 minutes. From Equation 6-1, this is similar to the flame residence time of a piece of round wood with a diameter of about 6.8 mm. The mean flame residence time of moving backfires in similar litter fuel quantities in the laboratory experiments described in the following chapter (Chapter 7) is about 24 seconds, which is equivalent to a piece of round wood 5.8 mm in diameter (from Equation 6-1). The residence time of moving flames studied in the field (Chapter 8) was variable, but for a litter fuel of 10 t ha^{-1}, the mean is about 50 seconds. This is equivalent to the residence time of a round wood particle of 8.5 mm in diameter on the gauze platform and 5.0 mm in diameter on the load cell platform. On this basis, it is reasonable to conclude that a high proportion (90%) of fuels less than 6 mm are consumed in the flaming zone, and therefore contribute most to frontal fire behaviour. Although the level of contribution of fuel elements will vary depending on the composition and structure of the fuel bed, the data presented in this study provide a sound basis for standardising litter fuel sampling in jarrah forests to leaves and round wood < 6 mm in diameter. This also conforms to the standard measure used in the McArthur

Meter (Cheney 1981) which was probably estimated from field observations.

Jarrah forest litter is comprised mainly of leaves and twigs < 6 mm in diameter (Chapter 5). There are significant quantities of large limbs and logs but these are scattered and very slow burning and although they make only a small contribution to flaming zone rate of spread and intensity they have important localised impacts in terms of soil heating and damage to tree boles. This is discussed in Chapters 11 and 12.

The residence time and combustion rate of fuel beds can be altered by compacting or aerating the fuel bed, thereby changing its porosity (Goss 1962, Block 1971, Rothermel 1972, Thomas 1974, Albini 1976 and Anderson 1990). Most workers (e.g. Smith and Thomas 1970, Block 1971, Heskestad 1973, Frandsen and Schuette 1978, Wilson 1982 and Anderson 1990) have determined a parabolic relationship between fuel bed bulk density or packing ratio and rate of weight loss during combustion. Anderson (1990) has demonstrated that arranging square sticks to optimum porosity results in a higher burning rate, supporting the modelling of Albini (1976). The porosity of jarrah litter increases in the first four years after fire, then remains more or less constant (see Chapter 5). The litter is made up of small diameter material with high surface area-to-volume ratios, so is unlikely to be as severely affected by packing as fuel arrays of larger elements.

Moisture content did not significantly influence flame residence time of burning leaves during this study, although moist leaves took longer to ignite. McArthur (1967a) observed that in the field, residence time increased with increasing fuel moisture content and decreased with increasing wind speed. On the other hand, Cheney (1991) reported that flame residence time of round wood was independent of fuel moisture content. However, there is considerable evidence in the literature that moisture content does affect combustion rate. Rothermel's (1972) rate of spread prediction model incorporates equations relating the effect of fuel moisture content and moisture content of extinction on burning rate and Wilson (1985) has shown that moisture content of extinction is also related to the arrangement of the fuel bed. Combustion trials in the laboratory by Gill *et al.* (1978) showed that there was an inverse linéar relationship between rate of weight loss of various fuel types and moisture content and Ottmar (1987) and Anderson (1990) found that the presence of moisture in large fuel particles influenced the amount of material which burnt during flaming combustion. Anderson (1990) reported that the rate of mass loss was more variable at higher moisture contents and tended to decrease with increasing moisture and, in the field, Reinhardt *et al.* (1989) found the extent of diameter reduction to round wood to be inversely related to moisture content. It is likely that the influence of moisture content on flame residence time and rate of weight loss increases with increasing particle size.

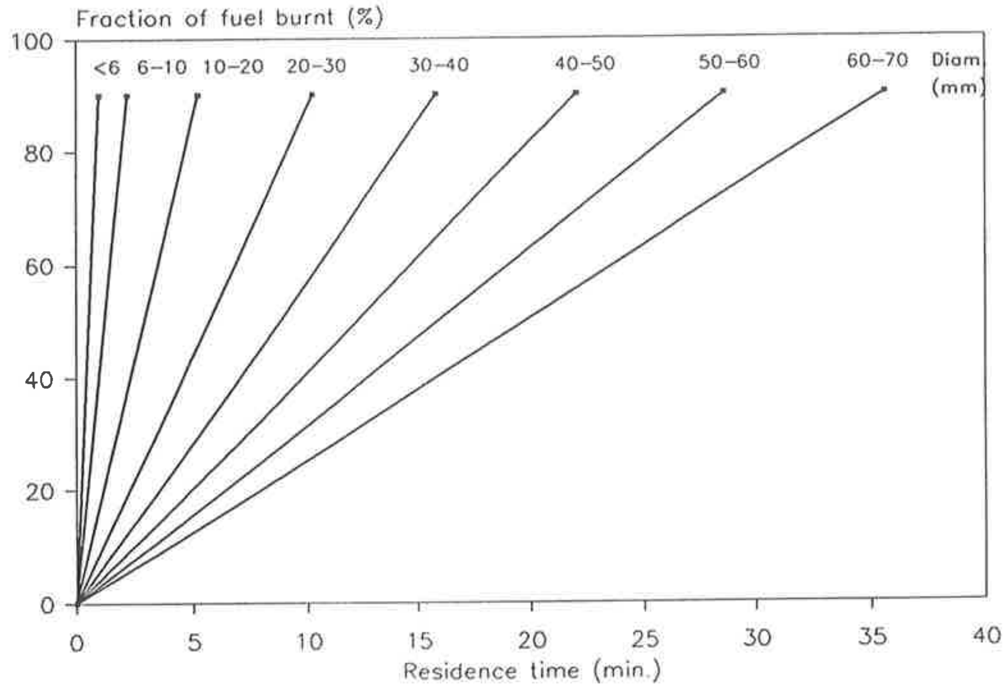
Cheney (1990a) prepared a nomogram for estimating the fraction of total fuel weight consumed in a forest fire based on the flame residence time and rate of weight loss of round wood particles of *Eucalyptus sieberi* burnt in an open hearth. He assumed 90% of each fuel class burns away under summer wildfire conditions. Based on results presented here, this is valid for fine fuels (<1-2 cm diameter). The combustion of larger fuels is less complete and more variable, both in the laboratory and in the field. Information about fuels consumed in the flaming zone is important for calculating expected fire intensity and is useful for preparing prescriptions and guide-lines for wildfire suppression and fuel reduction burning to reduce the hazard posed by wildfires. Following Cheney (1990a), a similar nomogram for jarrah fuels is shown in Figure 6-8. These calculations assume 90% combustion of fuels, so represent the optimum situation.

6.5 Concluding discussion

The shape and dimension of a fuel particle significantly affects its combustion rate with fine round twigs < 6 mm in diameter and leaves being the most flammable. The combustion properties of jarrah forest litter will be influenced by the size class composition of these elements, particularly the fraction of fine round twigs. This fraction steadily increases with fuel age until 10-15 years after fire, then stabilizes. Fuel quantity alone does not reflect the structure and composition of the litter, so in the absence of information about fuel age, forest type, cover and productivity, fuel quantity is not a reliable measure of the flammability of eucalypt fuels. Pieces of scattered, larger fuels with longer flame residence and burn-out times make a minor contribution to flaming zone behaviour but their quantity and distribution is likely to have an important impact on soil heating and damage to plant stems.

The preceding chapters examined jarrah forest litter fuel dynamics and elemental combustion properties. The way in which fire behaves in this fuel under varying conditions of fuel moisture content, weather and slope is examined in the following chapters.

Figure 6-8: Predicted fraction of the fuel burnt in various fuel size classes (diameter - mm) with flame residence time.



CHAPTER 7

FIRE BEHAVIOUR EXPERIMENTS IN THE LABORATORY

7.1 Introduction

Fire behaviour is the general term used to describe the way in which fires ignite, how fast flames spread, flame dimensions, energy outputs and fire shape and size (e.g., Brown and Davis 1973, Luke and McArthur 1978, Gill *et al.* 1981). An ability to make reasonably accurate fire behaviour predictions is essential for fire danger rating, wildfire suppression and for planning and implementing prescribed burns. Fire behaviour characteristics such as rate of spread, flame size, fire intensity, flame residence time, fuel burn-out time and flame temperature histories are also linked to the various physical impacts of fire and subsequent ecological responses. These linkages, important to modern management of the jarrah forest, are examined in later chapters.

Existing eucalypt forest fire behaviour models were developed over a narrow range of conditions and make some important assumptions and extrapolations about aspects of fire behaviour with little supporting theoretical or statistical basis (see Chapter 4). These assumptions need to be validated, and where necessary, better functional relationships developed.

Laboratory studies are an important, safe and inexpensive adjunct to field studies to further the understanding of fire behaviour. While the effect of scale is uncertain, particularly with regard to equilibrium between fire behaviour and fuel and weather factors, fundamental relationships between the important fire behaviour characteristics such as rate of spread, flame dimensions, fire shape, and fire intensity can be examined in the laboratory. Since the pioneering work of McArthur (1962) and Peet (1972), there has been no detailed experimental and statistical examination of fire behaviour relationships for eucalypt forest litter fuels.

7.2 Aims

This study aims to model the statistical relationships between dependent and independent fire variables as described below. A definition of variables and symbols used is contained in the glossary in Appendix 2.

Dependent variables;

i) rate of fire spread (r_F for headfire and r_B for backfire)

ii) flame height (h_F), length (L), depth (D) and angle (A)

iii) fire intensity (I) (Byram 1959)

iv) heat load (H_L)

v) flame temperature at 10 cm above the fuel bed (T_{10})

vi) flame residence time (t_r)

vii) fuel burnout time (t_b)

viii) fire shape (L/W)

Independent variables;

i) fuel quantity (w)

ii) fuel depth (f_D)

iii) fuel moisture content (MC)

iv) wind speed (U)

v) slope (S)

7.3 Methods

The fire laboratory at the Department of Conservation and Land Management's Manjimup Research Station consists of a galvanised, steel framed shed with a concrete slab floor (Plate 7-1). The shed is 7 m x 5 m x 4 m high. The gable roof can be rolled open to allow smoke and the convection column to escape unimpeded. Louvres set into the walls near floor level can be opened to control ventilation.

Experimental fires were set on a "fire table", which was 4 m x 2 m and set 1.2 m above the floor (Figure 7-1). The table was constructed of a heavy box steel frame with a 20 mm thick asbestos top. Wind was generated by a bank of four variable speed domestic fans approximately 60 cm in diameter. The fans were mounted in line on a wooden frame. A light gauze was erected some 30 cm in front of the fans to further provide a turbulent air flow to reflect conditions in the forest (Anderson and Rothermel 1965). The fans were mounted on a jig and could be maintained at a constant distance from the flaming zone as the fires burnt down the length of the table. This was achieved by setting the wooden board on which the fans were mounted, on greased metal skids. An electric winch and pulley system enabled the fans to be hauled along the skids.

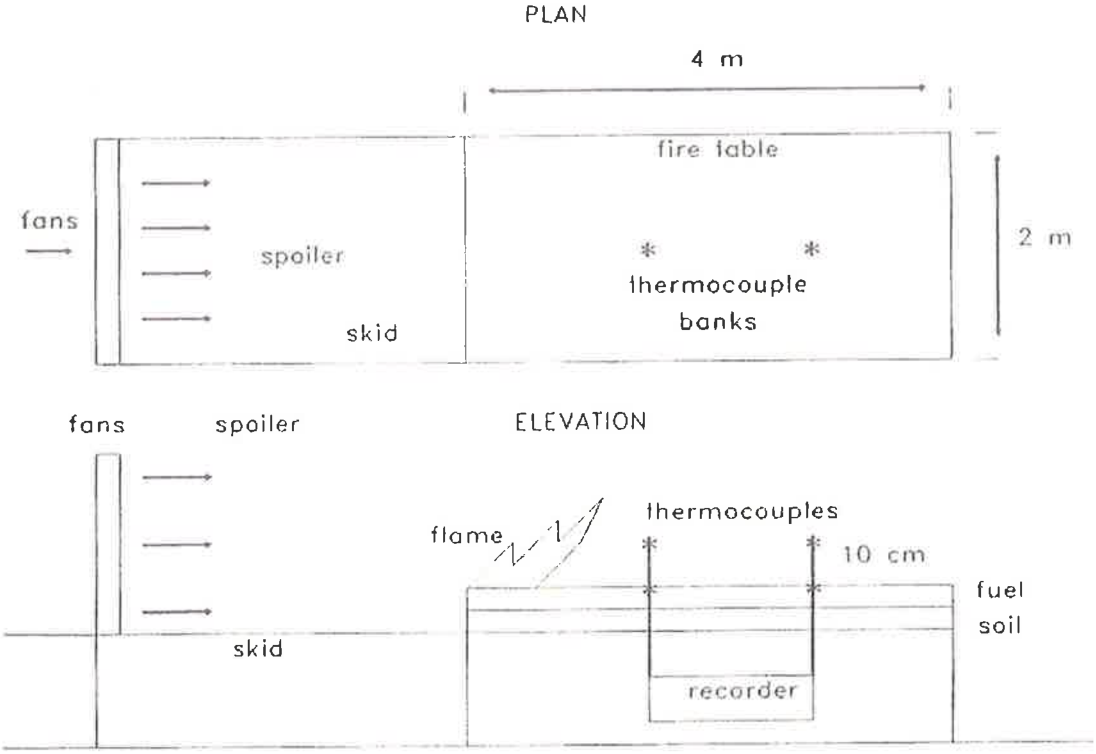
A metal pointer ensured the fans were maintained at a constant distance from the front of the flames. Wind speed was varied by either changing the speed of the fans, or by moving the fans closer to the flames. Wind speeds down the fire table were measured before any fires were set using two 50 mm sensitive cup type Cassella anemometers. For the various combinations of fan speed and distance of fans from the flames the actual wind speed at 20 cm above the surface of the table was measured by leaving the fans running in a set configuration (speed/distance) for two hours and then determining the mean wind speed from the anemometers. The anemometers were set up across the fire table some 70 cm apart. When the wind speeds for each combination of fan speed and distance from flaming zone had been determined, experimental fires were set without having to further measure wind speeds. Wind speeds above the height of the anemometers were not measured.

Fuel for the experimental fires consisted of fresh leaves and small twigs (L layer) < 6 mm in diameter collected from the floor of mixed jarrah and marri forests near Manjimup. The material was dried in an oven at 105^{o} C for 48 hours, weighed and distributed evenly over the fire table. The fuel bed was arranged to ensure that bulk density was as uniform as possible over the table and similar to natural forest litter bed fuels. Fuel depth at 20 positions was measured to the nearest millimetre and mean bulk density determined for each fire. Bulk density varied within and between fuel beds with the mean being 46.8 kg m^{-3}. It was not possible to increase the bulk density of low fuel quantities (28.6 kg m^{-3}) without physically breaking up the fuel particles. A reasonably consistent fuel bed was achieved by gently shaking the litter from oven drying bags and arranging the leaves on the table by hand. The fuel bed was then left for about three hours to cool and to reach a moisture equilibrium with atmospheric conditions inside the laboratory.

Fuel moisture content was varied by (i) natural variations in atmospheric temperature and humidity and (ii) wetting the fuels on a screen prior to arranging them on the fire table. During the series of backfire experiments, fuel moisture content was constant at about 8% of oven dry weight (odw). This was achieved by loading the oven with fuel and drying it as normal. After the drying process, the oven was opened for four hours and then sealed. This maintained fuel moisture at about 8%. Samples were collected from the fuel bed for determining moisture content. Fuel quantity (t ha^{-1} oven dry) was calculated from the known oven dry weight of fuel placed on the table.

Plate 7-1: The Department of CALM fire laboratory at Manjimup, W.A.

Figure 7-1. Layout of laboratory fire table used for studying fire behaviour in jarrah litter fuels.



To obtain data on fuel bed pre-heating and temperature history above the fuel bed, 30 gauge chromel-alumel wire thermocouples were fixed on the fuel bed surface and 10 cm above the fuel bed (Figure 7-1). In all, two sets of thermocouples were placed along the long axis of the table, at equal distances from the ends of the table and from each other. The thermocouples were not shielded against radiation and therefore provided a temperature history of whatever heat was being received by them. The thermocouple conducting cables were well insulated and about 1 cm of bare wire protruded to sense temperatures. Thermocouples were linked to a multi-channel chart recorder which provided a trace of temperature with time. Each probe was read every 2 seconds until thermocouple temperatures returned to within 5 ^{o}C of ambient temperature. The area beneath each thermocouple temperature history trace (the heat load (H_L), see glossary Appendix 1) was measured using a computerised digitising board; 1 cm^2 being equal to 40 ^{o}C x 12 seconds. The thermocouple technique proved to be a repeatable one for determining H_L as thermocouples were in a fixed position in relation to a homogeneous litter fuel bed.

Ambient air temperature and humidity inside the laboratory could not be controlled and were generally similar to conditions outside. The laboratory allowed control over wind speed and direction and could be sealed against rain, allowing experiments to be conducted over a range of external conditions. Experimental fires were conducted over the warmer, drier weather conditions of spring, summer and autumn.

Simultaneous and continuous line fire ignition was achieved by igniting a 2 m length of cotton wick soaked in methylated spirits. Fires were lit at one end of the table and allowed to burn for 50 cm before measurements were made. Headfires and backfires were studied by allowing flames to burn with the wind (headfires) or against a wind speed of 4.6 km h^{-1} (backfires). A series of zero wind fires were also studied. For backfires, fuel moisture content, slope and wind speed were held near constant at 8%, 0^{o} and 4.6 km h^{-1} respectively. Fuel quantity was varied in order to determine its effect on fire behaviour. Prior to ignition, a section of laboratory roof was rolled back to allow the convection column to escape.

A stop watch accurate to 0.01 seconds was used to measure the time taken for the fires to travel down the 4 m long table. Actual fire travel time was measured to the nearest second. A calibrated steel "L" shaped rod was used to measure flame height, length and depth from three positions on the table. Flame angle was measured from the side of flames using crude metal callipers and a protractor. The operator visually aligned one leg of the callipers with the leading edge of the flame and the other with the fuel bed. Several estimates were made during a fire and the mean angle used in regression analysis.

A small number of experiments (15) were conducted to examine the shapes of fires burning in eucalypt (jarrah/marri) leaf litter at different wind speeds. These fires were set in the laboratory on a larger table (3 m x 4 m) and were ignited from a point source. Fuel quantity and fuel moisture content were constant at about 8 t ha^{-1} and 8% respectively. A 35 mm still camera with motor drive was mounted vertically above the table and black and white photographs were taken when the fires had reached maximum size. The length and maximum width of each fire was measured off the photographs and the length-to-width ratio was regressed with wind speed. Due to the small scale of the laboratory fires, no attempt was made to examine fire acceleration from a point source. Recent laboratory studies by McAlpine (1988) and Green (1983) have provided useful information about fire acceleration and fire shape.

The effect of slope on the average rate of spread of jarrah litter fires, burning under zero wind conditions, was investigated by changing the inclination of a smaller fire table (1 m x 1.6 m) from -16^{o} through to $+16^{o}$ at 2^{o} increments. Fuel moisture and fuel quantity were held constant at about 8 % and 8 t ha^{-1} respectively.

7.3.1 Data Analysis

The first step was to generate Pearson correlation coefficients to identify relationships between variables. Secondly, scatterplots and three dimensional plots were generated to see if relationships were nonlinear. Finally, models were developed by regression analysis. Correlation coefficients (R^2) were generated for linear regressions as a measure of model fit. For zero intercept models, R^2 is computed from sum of squares values representing dispersion around zero and not around the mean of y, leading to artificially high values (Meyers 1989). Nonlinear relationships were modelled using nonlinear least squares fitting techniques (SAS Inc. 1985 and Meyers 1989) rather than transforming the data to linearize the model. Linearization of nonlinear models does not produce an equivalent model; transformation to linearize produces a different and unreasonable error structure and poorer properties of the parameter estimates (Meyers 1989). The goodness of fit of nonlinear models was determined from the standard error statistics and the coefficient of determination;

$$S = 1-(SS_{RES}/SS_{TOT}),$$

where S = coefficient of determination, SS_{RES} = sum of squares of residuals and SS_{TOT} = total sum of squares (corrected).

Residuals were also analysed to determine model underspecification or deviation from the homogeneous variance assumption. Measures of model bias and precision were determined from residual statistics by;

Error = (Residual/Predicted)*100,

Bias = mean of Error,

Precision = standard deviation of Error.

ANOVA tables for the main equations are contained in Appendix 1.

7.4 Results

Of the 122 laboratory fires, 54 were wind driven or headfires, 13 were backfires burning into wind (-4.6 km h^{-1}), 6 were fires burning under zero wind conditions, 15 fires were lit to examine fire shapes and 34 fires were set to examine the effect of slope on headfire spread rate.

The range of conditions experienced during the experimental fires are summarised in Table 7-1. The size of the laboratory facilities meant that fires were restricted to flame lengths of less than about 1.5 m. Flames in the field have been observed to exceed 10 m, so these laboratory fires were at the very low end of the range of potential surface fire behaviour in jarrah forest fuels.

TABLE 7-1: Variable bounds and descriptive statistics for 60 laboratory fires (wind speed >= 0 km h^{-1}) burning in jarrah forest litter fuel.

Variable	Units	Mean	Minimum	Maximum	Standard dev.
Rate of spread (r_F)	m h^{-1}	75.3	8.4	270.6	70.8
Flame height (h_F)	m	0.27	0.04	0.99	0.16
Flame length (L)	m	0.35	0.05	1.20	0.23
Flame depth (D)	m	0.32	0.02	1.45	0.38
Residence time (t_r)	s	13.3	5.0	32.0	6.15
Smoulder time (t_s)	s	119	18	300	62.3
Intensity (I)	kW m^{-1}	242	12	1123	247.0
Energy release (E_R)	kJ min^{-1}	24292	535	100997	26585
Fuel consumption (c_r)	kg min^{-1}	3.04	1.2	6.5	1.35
Temperature 10 cm (T_{10})	^oC	499	100	988	206.2
Fuel quantity (w_C)	t ha^{-1}	7.9	3.4	15.3	3.1
Fuel depth (f_D)	mm	17.4	4.0	50	8.4
Moisture content (MC)	%	7.6	3.0	14.0	2.4
Wind speed (U)	km h^{-1}	3.8	0.0	7.6	1.9
Temperature (T_A)	^oC	26.9	17	37	4.9
Relative humidity (RH)	%	38.5	18	80	11.6

7.4.1 Rate of spread

Headfires (i.e. wind driven) did not spread when fuel moisture content exceeded about 21% of oven dry weight or when fuel quantity was less than about 3.0 t ha^{-1}.

The quantity of fuel on the fire table had no effect on headfire rate of spread, as shown by the Pearson correlation matrix in Table 7-2 and the data graphed in Figure 7-2. Wind speed was the most important variable and fuel moisture content showed a weak but significant inverse correlation with rate of spread. At high wind speeds, the flames spread rapidly across the surface of the fuel bed. In deep and heavy fuel beds the wind driven flames burnt in the top 10-15 mm and sub-strata fuel either smouldered slowly after the passage of the main flame structure or remained as carbonised, charred and thermally degraded material which did not appear to ignite.

The vertical rate of spread (down through the fuel bed) calculated from flame residence time and fuel bed depth varied from 3.0-14.1 m h^{-1} with a modal value of 5 m h^{-1}.

Table 7-2: Pearson correlation coefficients for variables likely to affect headfire rate of spread of laboratory fires in jarrah litter fuel. The significance probability of the correlation, under the null hypothesis that the correlation is zero, is in parentheses.

Variable	Headfire rate of spread (r_F)
Wind speed (U)	0.94 (0.0001)
Fuel quantity (w_C)	-0.12 (0.364)
Fuel depth (f_D)	-0.03 (0.782)
Moisture content (MC)	-0.31 (0.022)

In contrast to Steward's (1974) and others findings, and in contrast to the wind driven fires studied here, the rate of spread of backfires was directly related to fuel quantity (constant moisture content) (see Figure 7-3). Backfires would not spread when fuel quantity was less than about 4.0 t ha^{-1}. Unlike wind driven fires, backfires burnt uniformly through the fuel bed. Vertical rate of spread ranged from 2.0-7.4 m h^{-1}, with most fires burning at about 4 m h^{-1} which is slightly lower than the value calculated for headfires (about 5 m h^{-1}).

Figure 7-2: Headfire rate of spread with fuel quantity by wind speed (U) classes. U at 20 cm above the fire table.

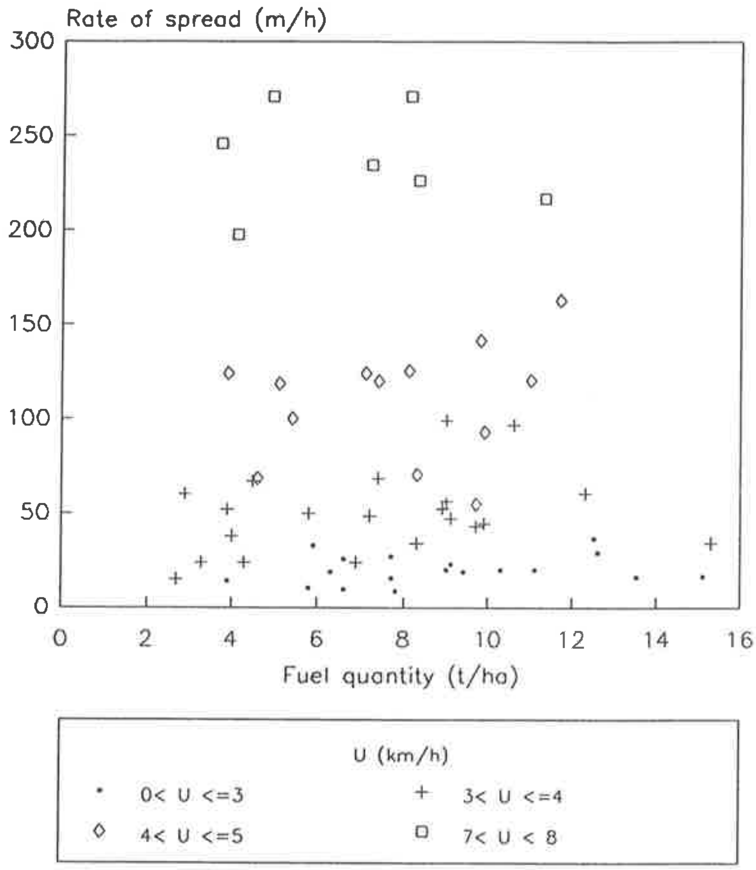
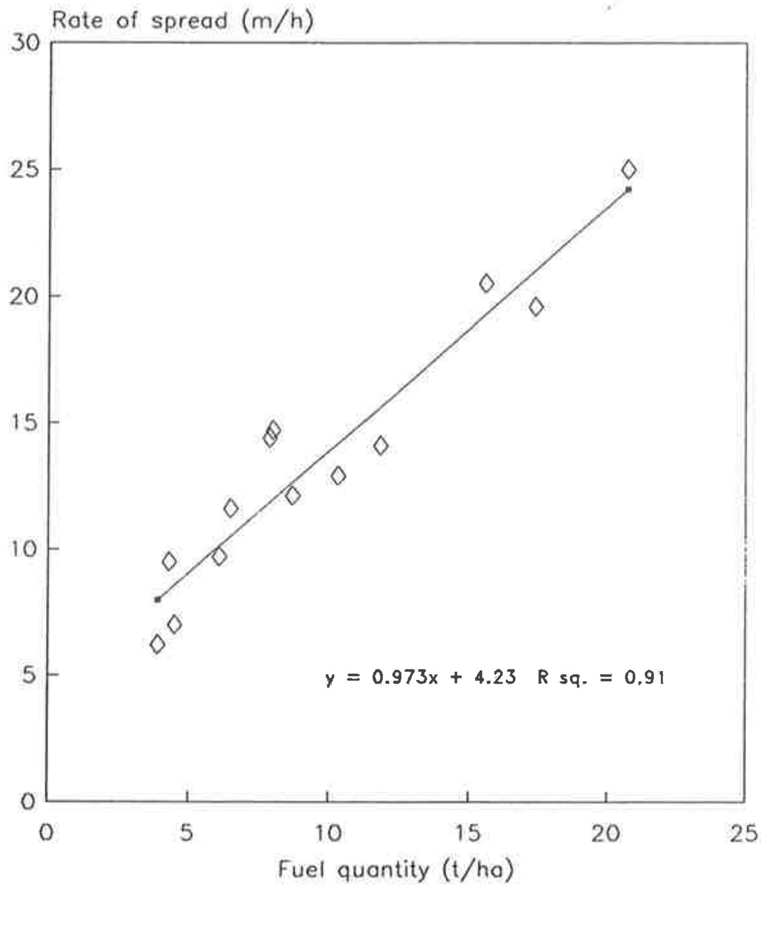


Figure 7-3: Backfire rate of spread with fuel quantity consumed. Wind speed (U) = -4.6 km/h and fuel moisture (MC) = 7-8% of odw.



Headfire rate of spread is graphed with wind speed, the most dominant variable influencing rate of spread, in Figure 7-4. Other variables such as fuel moisture content are not controlled. Both exponential and power equation forms were fitted to the data. A power form provided the best fit over the entire range of conditions of wind speed and fuel moisture content (Table 7-3).

Headfire rate of spread was relatively insensitive to wind speeds below about 3.5 km h^{-1} but increased sharply as wind speed increased above this level. This represented the transition from convection dominated fires to wind driven fires, as evidenced by the flame angle. At low wind speeds, the flames were more or less vertical and the fire spread slowly whereas at higher wind speeds, the flames were tilted and the fires spread faster. Above this "threshold" wind speed, a strong linear relationship existed between rate of spread and wind speed (Figure 7-4, Table 7-3). However, attempting to fit all data (including low wind speed data) to a linear model resulted in a poor fit with a low R^2 value, poor precision and considerable bias (Equation 1 in Table 7-3). The linear model (Equation 2 in Table 7-3) for wind speeds > 3.0 km h^{-1}, but which ignores fuel moisture content, shows poor precision even though the R^2 value is relatively high. Equation 3, in the same group but for low wind speeds (<= 3.0 km h^{-1}), was a poor fit using wind speed alone, probably because both fuel moisture content and quantity affect rate of spread at low wind speeds as shown by the backfire data above.

Figure 7–4: Headfire rate of spread with wind speed. Three equation forms are fitted to the data. Equation numbers refer to the equations in Table 7–3.

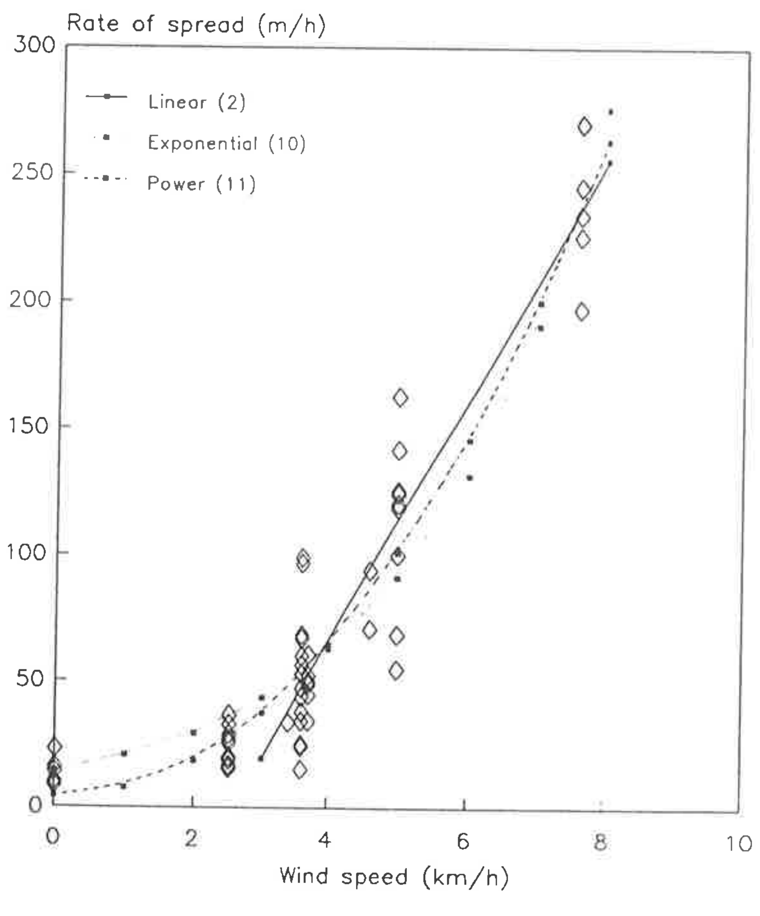
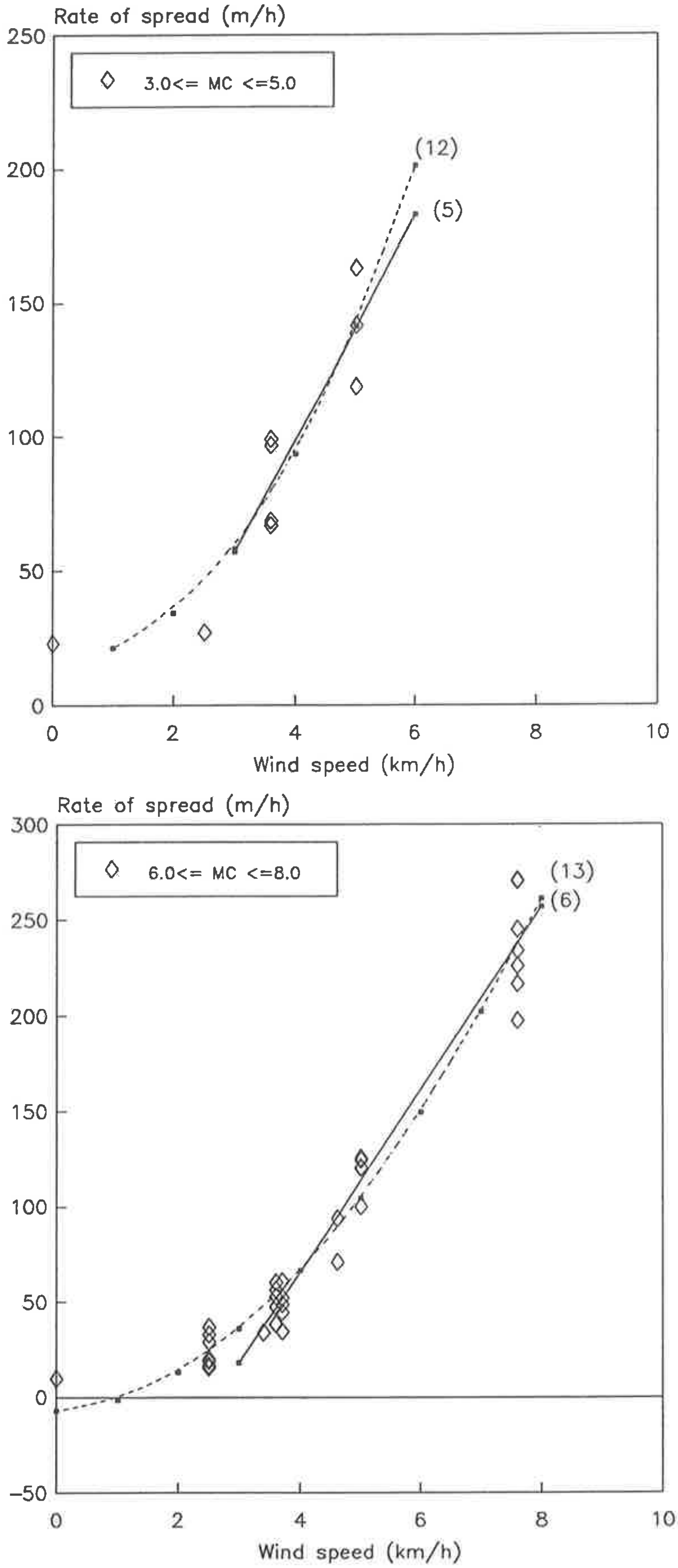


Figure 7-5: Headfire rate of spread with wind speed by fuel moisture content classes. Linear regressions are fitted for wind speed > 3.0 km/h. Equation numbers refer to equations in Table 7-3.



The effect of wind speed alone (including zero wind) on headfire rate of spread was analysed by stratifying the data set according to the fuel moisture content classes shown in Figure 7-5. These data were again stratified as either above or below a wind speed of 3.0 km h^{-1} and linear models fitted. There were insufficient data points to attempt linear regression by moisture content classes for U < 3.0 km h^{-1} wind speed class, so all moisture contents were included in this analysis. Both linear and non-linear equation forms were compared to determine the best fit model. Power equations best fitted the data for all wind speeds, but a strong linear relationship existed for data sets where U > 3.0 km h^{-1}. Equation forms, parameter estimates and measures of the goodness of fit of models are summarised in Table 7-3. While both linear and nonlinear equation forms predict similar rates of spread over the range of experimental data, there is strong divergence on extrapolation to high wind speeds.

Table 7-3: Summary of equation forms and parameter estimates for predicting headfire rate of spread (r_F) from wind speed (U) for various moisture content (MC%) and wind speed classes. N = equation number and refers to equations graphed in Figures 7-5 and 7-6. n = number of observations. Regressions are unbiased if the absolute value of bias = 0 and precise if the precision value = 0.

N	MC	n	U	Equation	R^2	Residuals Range	Residuals Mean	Error Bias	Error Precision
GROUP 1: Linear models, MC not controlled									
1	3-14	60	>0.0	$r_F = 31.7(U) -44.7$	0.76	-59.2-74.3	0.04	-28.7	45.5
2	3-14	42	>3.0	$r = 47.4(U) -123.1$	0.87	-59.1-51.6	0.00	0.26	35.3
3	3-14	18	<3.0	$r_F = 3.9(U) +13.4$	0.33	-8.0-13.4	0.00	0.00	32.0
GROUP 2: Linear models, MC partially controlled									
5	3-5	7	>3.0	$r_F = 41.6(U)-67.2$	0.75	-22.3-21.8	0.00	0.00	17.47
6	6-8	26	>3.0	$r_F = 47.7(U)-125.0$	0.95	-40.5-32.7	0.01	0.12	14.68
7	9-15	9	>3.0	$r_F = 22.8(U)-51.9$	0.60	-15.2-17.3	0.00	0.22	33.72
GROUP 3: Non-linear models, MC not controlled									
10	3-14	60	>0.0	$r_F = 14.3e^{0.37U}$	0.88	-45.5-70.5	1.50	-7.80	36.10
11	3-14	60	>0.0	$r_F = 3.2U^{2.10}+4.3$	0.90	-39.6-33.5	0.19	0.08	11.45
GROUP 4: Non-linear models, MC partially controlled									
12	3-5	9	>0.0	$r_F = 3.7U^{2.18}+17.5$	0.87	-22.4-21.7	0.72	1.68	24.03
13	6-8	35	>0.0	$r_F = 5.5U^{1.87}-7.2$	0.96	-41.4-31.7	0.17	-8.70	44.51
14	9-15	16	>0.0	$r_F = 0.4U^{2.9}+12.7$	0.76	-16.1-17.2	0.14	0.46	28.75

The form of the relationship between rate of spread and fuel moisture content varies with physical fuel properties. For example, Rothermel and Anderson (1966) reported a linear relationship between rate of spread and fuel moisture for ponderosa pine and white pine needles. Van Wagner (1967) and McArthur (1977) found that a curvilinear relationship was a better fit for red pine needles and for grassland fuels respectively.

The relationship between headfire rate of spread and fuel moisture content for jarrah litter fuels was determined by firstly stratifying the data according to wind speed classes then fitting various equations, as shown in Figure 7-5. Equation details are provided in Table 7-4. There were insufficient data over a range of moisture contents at high wind speeds ($U > 6.0$ km h^{-1}) to warrant analysis. The relationship was a poor one at low wind speeds ($U < 3.0$ km h^{-1}), probably because of the influence of fuel quantity on the rate of spread of convection dominated fires. Based on S (goodness of fit), and error values (Table 7-4), power and inverse functions fitted the data equally well and better than other forms. However, power functions result in dangerously high extrapolations at low moisture contents so the inverse was the preferred form (Equations 11 and 12 in Table 7-4).

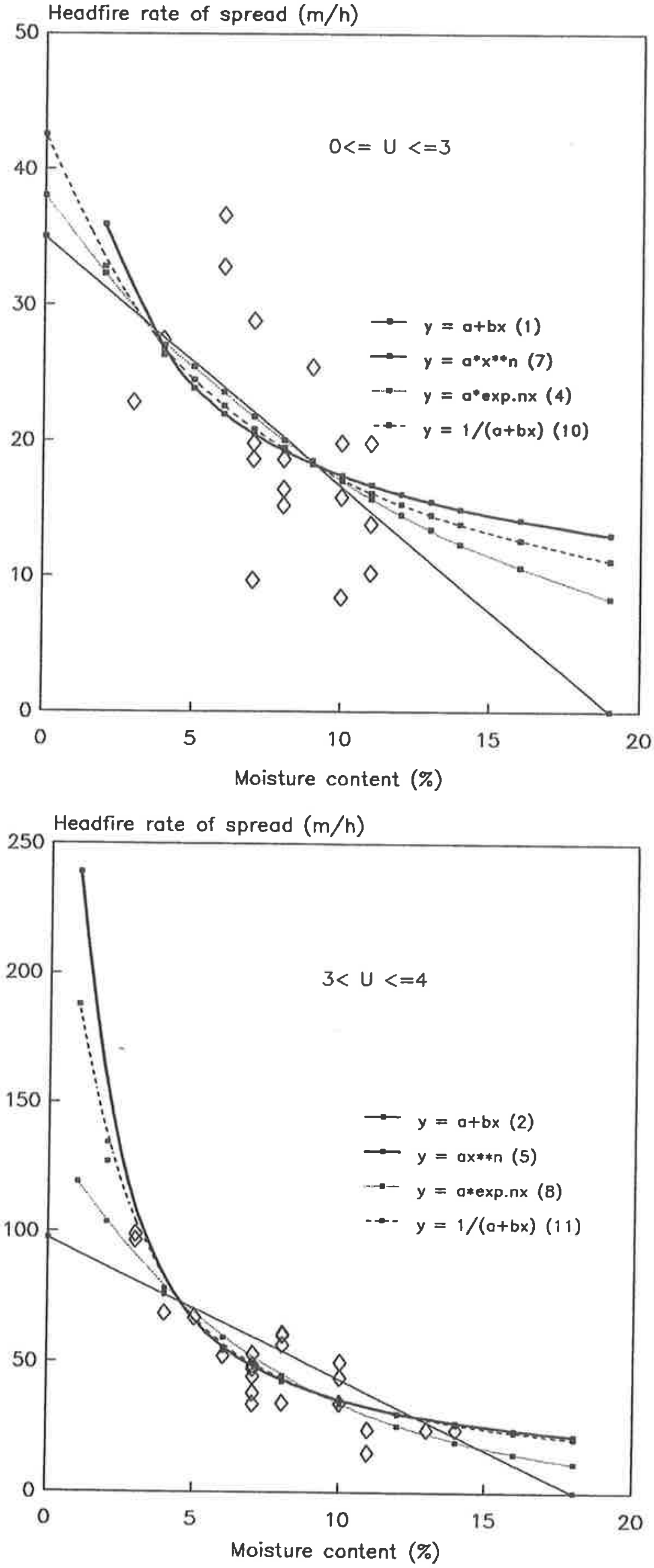
Table 7-4: Summary of equation forms and parameter estimates for predicting headfire rate of spread (r_F) from fuel moisture content (MC%) and controlling wind speed (U). N = equation number and relates to equations graphed in Figure 7-6. n = number of observations. For nonlinear regressions, R^2 = S. Regressions are unbiased if the absolute value of bias = 0 and precise if precision = 0.

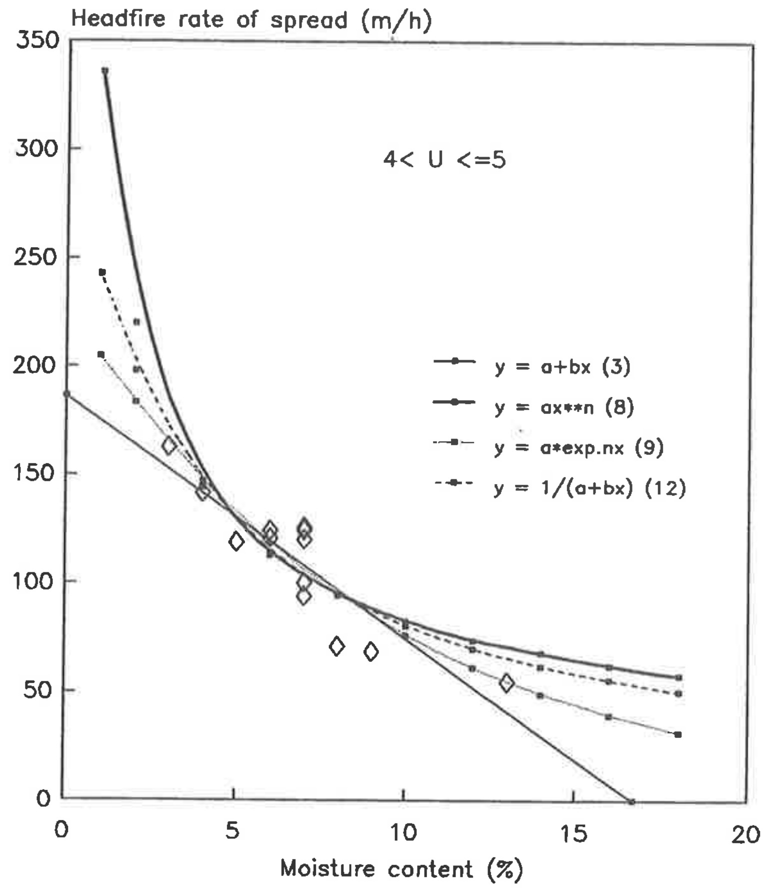
N	MC	n	U	Equation	R^2	Residuals Range	Residuals Mean	Error Bias	Error Pecision
				Group 1: Linear functions					
1	3-11	18	0.0-3.0	$r_F = 34.7-1.85(MC)$	0.30	-12.2-12.9	-0.04	-0.37	31.7
2	3-14	22	3.1-4.0	$r_F = 97.6-6.18(MC)$	0.69	-20.6-19.9	0.07	4.40	35.3
3	3-13	13	4.1-5.0	$r_F = 186.3-11.2(MC)$	0.78	-25.9-17.5	-0.02	0.96	16.4
				Group 2: Non-linear functions					
4	3-14	18	0.0-3.0	$r_F = 49.1MC^{-0.45}$	0.22	-10.8-14.6	-0.05	-0.84	33.7
5	3-14	22	3.1-4.0	$r_F = 239.0MC^{-0.83}$	0.79	-17.6-18.0	0.32	0.24	24.6
6	3-13	13	4.1-5.0	$r_F = 335.6MC^{-0.61}$	0.74	-23.6-22.9	-0.47	-1.10	16.6
7	3-13	18	0.0-3.0	$r_F = 38.0e^{-0.08MC}$	0.29	-12.1-13.0	-0.06	-3.00	31.4
8	3-14	22	3.1-4.0	$r_F = 137.1e^{-0.14MC}$	0.77	-17.8-15.9	-0.07	0.90	24.6
9	3-13	13	4.1-5.0	$r_F = 228.6e^{-0.11MC}$	0.80	-24.0-19.5	-1.40	-1.58	13.2
10	3-13	18	0.0-3.0	$r_F = 1/(0.00235+0.00348MC)$	0.26	-11.2-14.0	-0.11	-1.21	32.7
11	3-13	22	3.1-4.0	$r_F = 1/(0.00278+0.00255MC)$	0.79	-17.4-17.4	-0.43	-0.60	24.2
12	3-13	13	4.105.0	$r_F = 1/(0.00319+0.000928MC$	0.77	-23.4-22.2	-0.47	-1.14	15.0

At higher wind speeds and low moisture contents, the linear equation under predicted rate of spread and gave a projected moisture content of extinction of about 17% odw, which is about

4% below that determined from experimentation (Figure 7-6).

Figure 7-6: Headfire rate of spread with fuel moisture by wind speed (U - km/h) classes. Equation numbers refer to equations in Table 7-4.





Based on the best fit regressions described in Tables 7-3 and 7-4, a nonlinear least squares fitting technique (SAS Institute 1985) was used to derive the best fit single equation for predicting headfire rate of spread (r_F) from wind speed (U) and fuel moisture content (MC) together. For the entire range of data, including zero wind speed, the following equation was derived. Parameter standard errors are in parentheses and regression ANOVA is contained in Appendix 1.

$r_F = (0.0245(U)^{2.22}+0.071)*(1/(0.003+0.000922(MC)$ (Equation 7-1),
(0.0075) (0.142) (0.050) (0.00029)

Residual range = -43.9-50.4, Mean residual = 0.17, Bias = 5.20 and Precision = 39.58.

Observed rate of spread is graphed with rate of spread predicted by Equation 7-1 in Figure 7-7. Residuals (observed-predicted) and residual statistics are plotted with observed rate of spread in Figure 7-8. There is evidence of model underspecification over the mid and high range of rates of spread. The error variance is not constant, but increases with rate of spread (Figure 7-8). This probably reflects the scaling problems associated with laboratory studies; spread rate had not reached equilibrium at high wind speeds.

Figure 7-7: Observed headfire rate of spread (r) with r predicted using Equation 7-1.

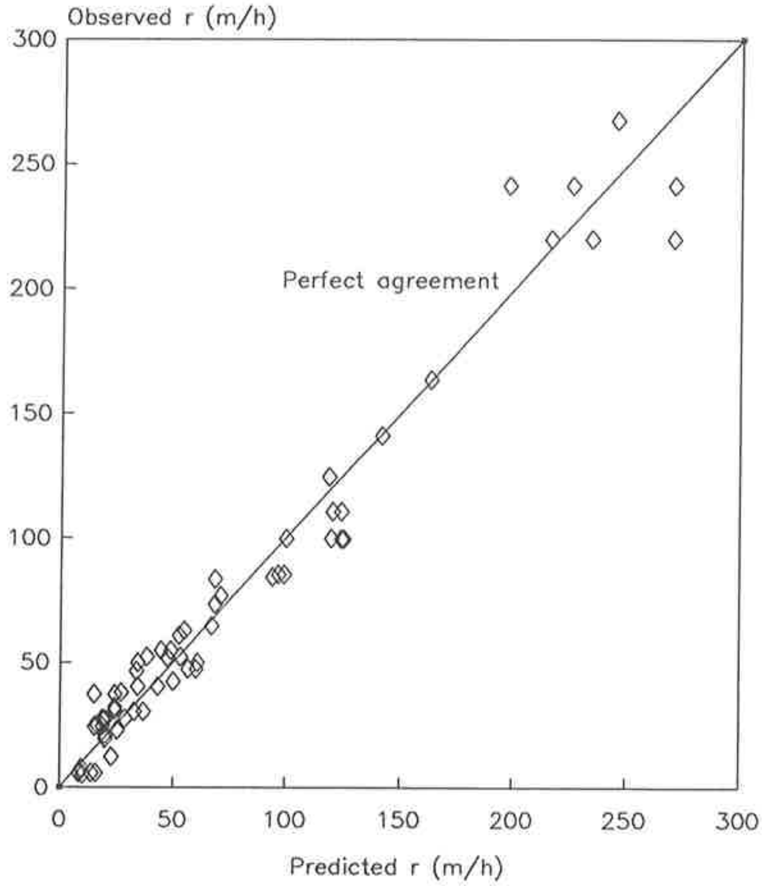
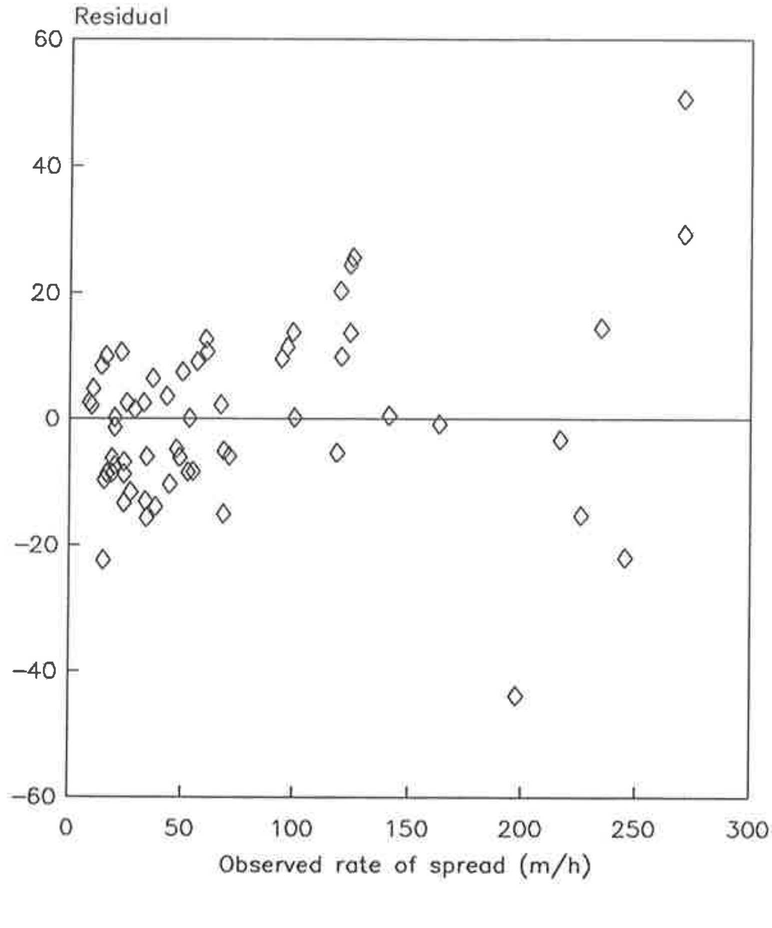


Figure 7-8: Residuals (observed-predicted) with observed rate of spread.



7.4.2 Flame Dimensions

Flame height, length and depth are weakly related to rate of spread as shown in Figure 7-9, indicating that large flames are not necessary for high rates of spread and that flame size was not a primary causal factor affecting rate of spread. Flame height tends to plateau beyond a rate of spread of about 100 m h^{-1}, supporting the observation that flames were driven across the surface of the fuel bed and that sub-strata fuels contributed little to the flame front at higher wind speeds. This phenomenon may have been exaggerated in the small laboratory fires where fires fanned by strong winds were in an early build-up phase. Given sufficient time and space, a deeper flaming zone would develop as the fire burnt down into the fuel bed behind the flame front, creating a strong convection column centred further behind the leading edge. This would tend to hold the flames up, retarding their spread across the fuel bed surface.

Flame length and depth, although variable, increased linearly with increasing wind speed and rate of spread. Most variation (62-67%) in flame size was explained by wind speed, the quantity of fuel consumed and to a lesser extent, fuel moisture content (Table 7-5). Large flames did not cause high rates of spread but were a consequence of strong wind, high quantity of fuel consumption and dry fuels. Stepwise linear models relating flame dimensions with these variables are summarised in Table 7-5. Variables in the model are significant at the 0.15 level.

Table 7-5: Linear regression models of the dependency of flame dimensions (m) on wind speed (U, km h^{-1}), fuel quantity consumed (w_C, t ha^{-1}) and fuel moisture content (MC, % of oven dry weight).

Dependent Variable	Independent Variable	Parameter estimate	Standard error	Partial R^2	Model R^2
Flame height	w_C	0.0322	0.005	0.32	0.32
	U	0.041	0.006	0.28	0.60
	MC	-0.009	0.005	0.02	0.62
	Intercept	-0.013	0.067		
Flame Length	U	0.079	0.009	0.47	0.47
	w_C	0.038	0.006	0.20	0.67
	MC	-0.007	0.007	0.02	0.69
	Intercept	-0.044	0.046		
Flame depth	U	0.147	0.015	0.59	0.59
	w_C	0.033	0.011	0.05	0.64
	Intercept	-0.194	0.063		
	MC did not meet model entry requirements				

Figure 7-9: Flame length with headfire rate of spread.

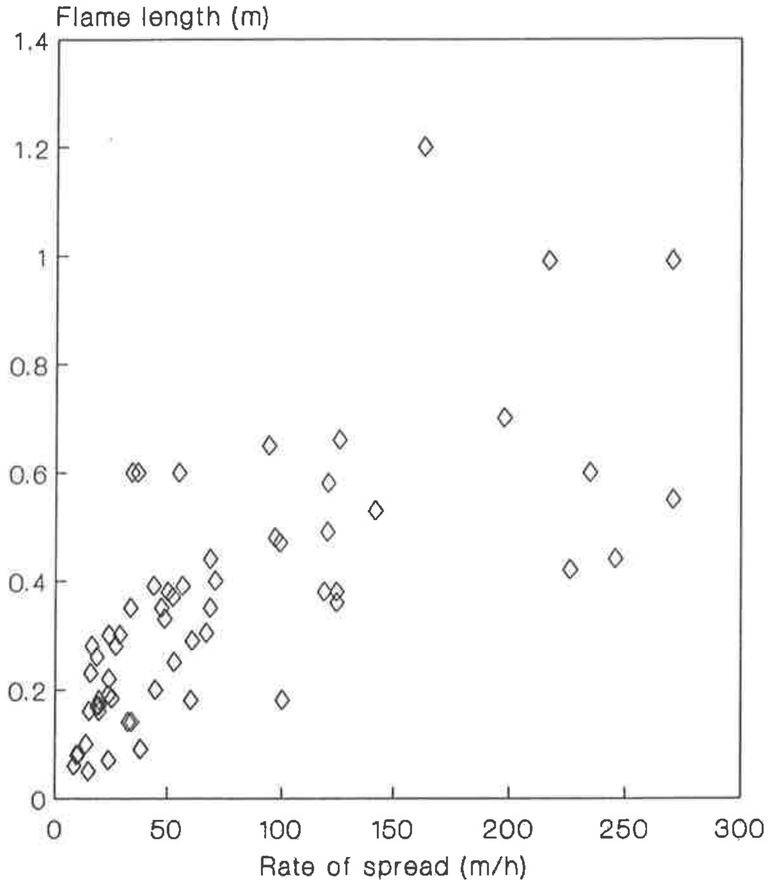
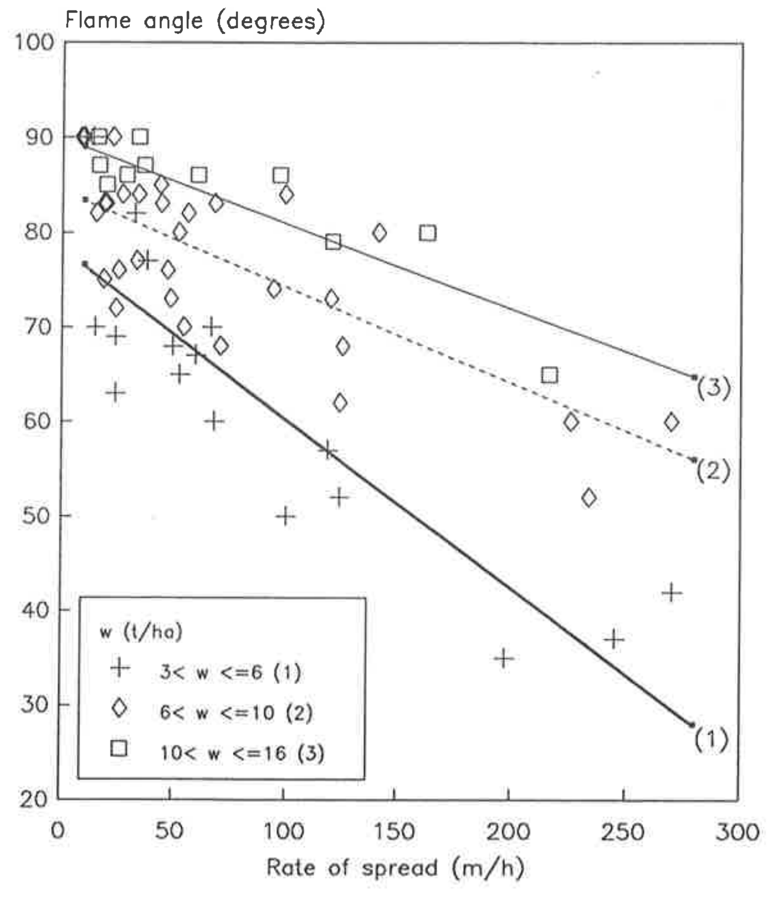


Figure 7–10: Flame angle as a function of rate of spread and quantity of fuel consumed (w).



As headfire rate of spread (r_F) is mainly a function of wind speed and fuel moisture content (Equation 7-1), it can be substituted for these variables and used with fuel quantity consumed (w_C) to predict flame dimensions (Equation 7-2, 7-3 and 7-4). In these equations the regressions were forced through the origin resulting in re-defined R^2 values. Headfire flame angle (A) varied inversely with wind speed and with headfire rate of spread but directly with fuel quantity (w_C) (Figures 7-10 and 7-11). Wind speed accounted for 63% and fuel quantity 20% of the variation explained by Equation 7-5, and rate of spread accounted for 51% and fuel quantity 23% of the variation explained by Equation 7-6. Hamada (1952) reported flame angle in building fires to be a function of wind speed squared then divided by four times flame depth. Laboratory studies by Szczygiel (1988) using scotch pine litter, produced an inverse relationship between flame angle and wind speed.

$$h_f = 0.0013(r_F)+0.0328(w_C) \qquad R^2 = 0.88 \qquad \text{(Equation 7-2)}$$

$$L = 0.0024(r_F)+0.036(w_C) \qquad R^2 = 0.90 \qquad \text{(Equation 7-3)}$$

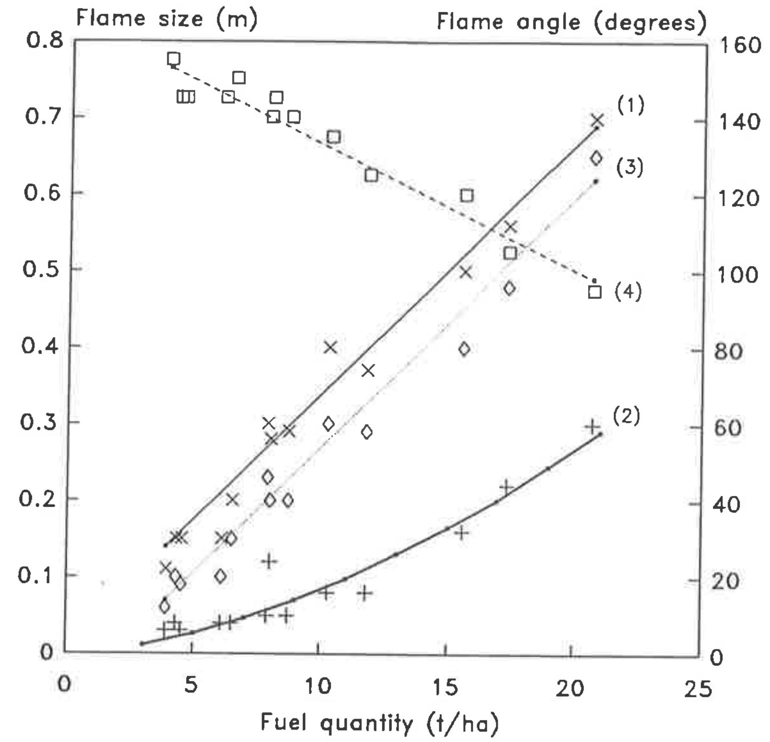
$$D = 0.0046(r_F)+0.028(w_C) \qquad R^2 = 0.85 \qquad \text{(Equation 7-4)}$$

$$A = -5.08(U)+2.01(w_C)+77.4 \qquad R^2 = 0.83 \qquad \text{(Equation 7-5)}$$

$$A = -0.13(r_F)+2.18(w_C)+66.5 \qquad R^2 = 0.74 \qquad \text{(Equation 7-6)}$$

The linear regressions in Figure 7-11 define the theoretical threshold wind speed for a wind driven fire as between 1-2 km h^{-1} depending on fuel quantity; the threshold increasing with fuel quantity. This assumes that a fire is wind driven when $A < 90^o$. Based on visual observations of the experimental laboratory fires, the threshold was estimated to be closer to 3 km h^{-1} for moderate fuel quantities (6.0-10.0 t ha^{-1}). Backfire flame length, flame depth and flame height were directly related to fuel quantity, hence rate of spread (Figure 7-12). Backfire flame angle (between flame face and the unburnt fuel bed) was inversely related to fuel quantity (Figure 7-11) with flames approaching vertical with increasing fuel quantity. The high correlation coefficients (Figure 7-11) reflect the ease of measuring the small, discrete backfire flames.

Figure 7–12: Backfire flame height, flame length and flame angle with the quantity of fuel consumed. Fuel moisture = 7–8% and fires burning into a wind speed of 4.67 km/h.



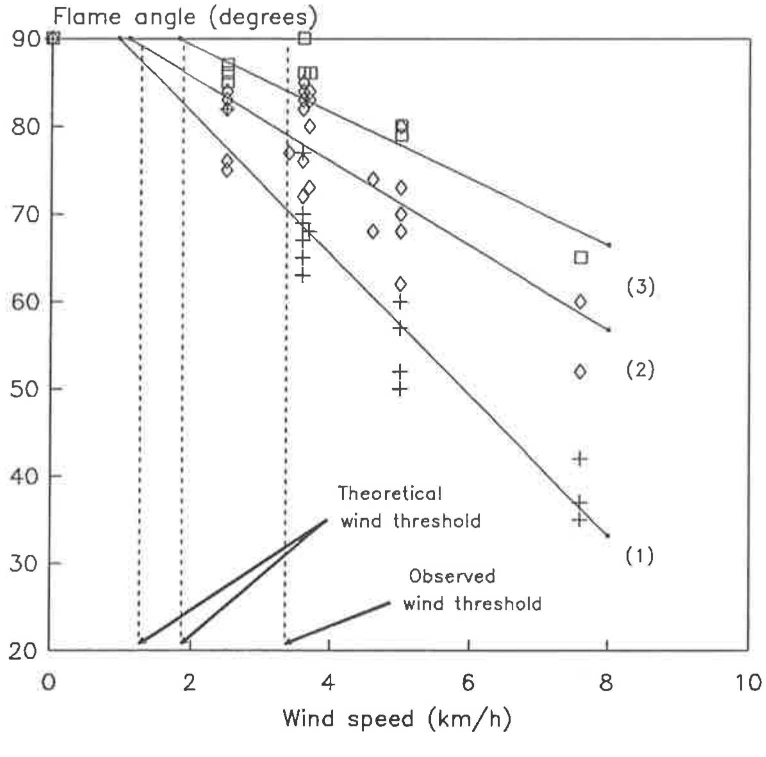
× Length (1) + Depth (2)

◇ Height (3) □ Angle (4)

$Y = 0.033X+0.012 \quad R^2 = 0.97$ (1) $Y = 0.0018X^{1.67}$ (2)

$Y = 0.0323X-0.049 \quad R^2 = 0.97$ (3) $Y = -3.28X+166.0 \quad R^2 = 0.94$ (4)

Figure 7–11: Flame angle as a function of wind speed and quantity of fuel consumed. The theoretical wind speed at which fires become wind-driven is shown with the observed wind speed at which fires become wind driven.



+ 3< w <=6 (1) ◇ 6< w <=10 (2)

□ 10< w <=16 (3)

7.4.3 Fire intensity

Byram's fireline intensity (Byram 1959) is widely used to describe the energy output or the power of a fire. It has often been described as the single most important characteristic of a fire's general behaviour (Van Wagner 1970b and Alexander 1982). It is used as a measure of suppression difficulty, to set limits for prescribed burning, and as a measure of the direct impact of fire on above ground vegetation (e.g., Cheney 1981, Andrews and Rothermel 1982 and Cheney 1990a). Fire intensity is calculated by:

I = Hwr (Byram 1959),

where H is the fuel low heat of combustion (18,700 kJ kg^{-1} used here), w is the weight of fuel consumed in the flaming zone and r is flame rate of spread. Intensity (I) is usually expressed in kilowatts per metre. Alexander (1982) provides a detailed description of how to calculate and interpret fire intensity.

Fire intensity is also directly related to flame dimensions and can be used to calculate flame length or vice versa (e.g., Byram 1959, Sneeuwjagt and Frandsen 1977, Luke and McArthur 1978, Rothermel and Deeming 1980, and Nelson and Adkins 1986). Field experiments have generally resulted in good agreement with Byram's (1959) original relationship between flame length and fire intensity (e.g. Van Wagner 1968a, Thomas 1971, Sneeuwjagt and Frandsen 1977). However, Nelson and Adkins (1986) found that flame length in their laboratory fires was more or less constant at 0.5 m, regardless of fire intensity, whereas in the field flame lengths were proportional to the square root of fire intensity. They concluded that further studies were needed to resolve the relationship between flame characteristics and fire intensity.

The weight of fuel consumed in the flaming zone, w_C, is a vital but difficult to measure component of the intensity equation. It is generally accepted that fine fuels less than 6 mm in diameter are mostly consumed in the flaming zone of a forest fire (see Chapter 6). However, during these laboratory experiments, it was visually evident that a significant proportion of the fuel bed, especially of deeper (heavier) fuel beds burning under high wind speeds, was not burnt in the flaming zone, but burnt as either "flickering", glowing or smouldering combustion after the passage of the main flame structure. It appeared that most active flaming combustion was associated with the top 15-20 mm of the fuel bed, as discussed in section 7.4.1. This phenomenon has been observed for other well packed fuel beds and coarse, woody fuel particles (e.g., Kiil 1971, Alexander 1982 and Cheney 1990a). This is unlikely to be an artifact of small scale laboratory studies although the effect may have been exaggerated under conditions of high fuel quantity and high wind speeds as fires would not have reached a quasi steady state.

Alexander (1982) suggested reducing the total fuel quantity consumed in the flaming zone in these situations, but did not provide details on how this should be done.

To examine the relationship between flame size and fire intensity for jarrah litter fuels, fire intensity was calculated two ways by deriving two measures of fuel quantity consumed in the flaming zone.

Method 1: The first calculation was based on the generally accepted premise that almost all fuel less than 6 mm in diameter is consumed in the flaming zone. Thus, intensity was calculated from the fuel quantity consumed (w_C)(t ha^{-1}), determined from total fuel quantity (W) less residue after combustion (r) and rate of spread (r_F) (m h^{-1}). Thus;

$I = (W\text{-}r)*r_F*0.516$,

where I = intensity (kW m^{-1}), W = total fuel < 6 mm diameter (t ha^{-1}), r = fuel residue (t ha^{-1}), r_F = rate of spread (m h^{-1}).

The quantity of fuel residue (material remaining on the fire table after all combustion had ceased) was a function of the total fuel quantity and wind speed. The proportion of the total fuel quantity consumed by all forms of combustion (total quantity on the table minus residue/total quantity) was dependent on the headfire rate of spread (therefore wind speed and fuel moisture content). When rate of spread exceeded about 60 m h^{-1}, the proportion of fuel consumed was more or less constant at about 85% of the total fuel quantity.

Method 2: This estimate of intensity (I) is based on calculating the quantity of fuel actually consumed in the flaming zone using flame residence time, flame depth and the combustion rate of litter fuel particles derived in Chapter 6, i.e.;

i) $W_{CZ} = D*K*(W*0.1)$

ii) $C_{CZ} = W_{CZ}*(t_r*L)$

therefore,

iii) $I = (C_{CZ}/(F_D*2))*W_H/3600*18{,}700$

where W_{CZ} = potential weight of fuel in the combustion zone (kg), D = flame depth (m),

W = total fuel quantity (t ha^{-1}), K = the width of the fire table (2 m in this case), C_{CZ} = the actual weight of fuel consumed in the flaming zone (kg), t_r = flame residence time (s), c_F = fuel combustion rate (0.017 kg s^{-1} kg^{-1} of initial fuel; from Chapter 6).

Intensities calculated using both methods were quite different but related to flame length reasonably well, as shown in Figure 7-13. Byram's equation is also graphed for comparison. The best fit regressions of fire intensity with flame length for both methods were;

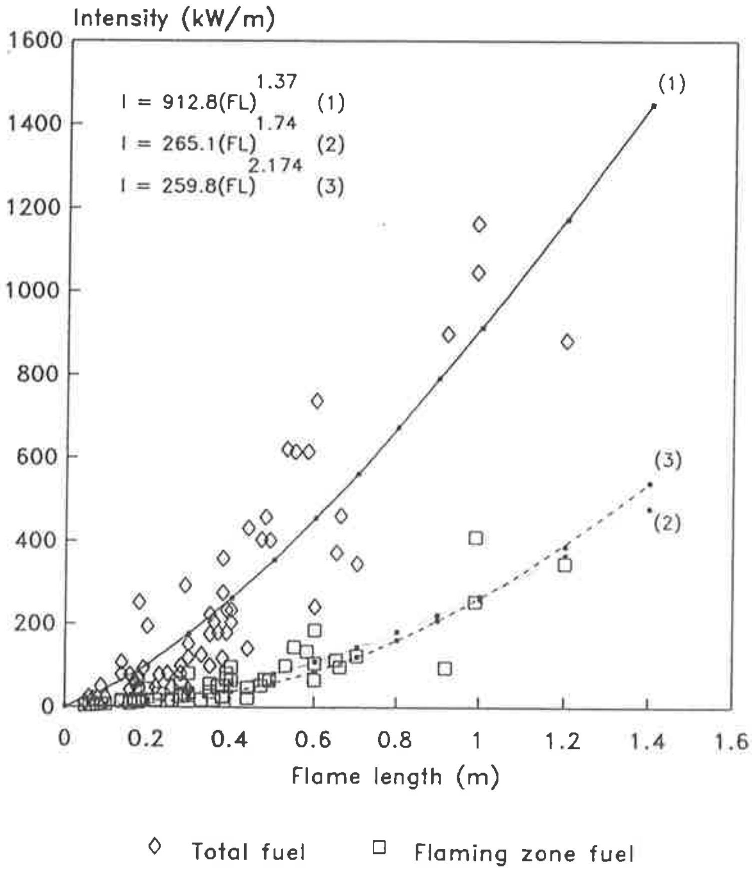
Method 1: $I = 912.8(L)^{1.373}$ (Equation 7-7)

Method 2: $I = 265.1(L)^{1.745}$ (Equation 7-8)

7.4.4 Flame residence and fuel burn-out time

It was difficult to measure the residence time of headfire flames from the thermocouple traces alone. Thermocouple temperature rose sharply as flames approached the sensors, but the decay curve was gradual. The "event markers" on the thermocouple chart print-out, which were based on visual observations, provided better estimates of residence time.

Figure 7–13: Fire intensity calculated using (1) total fuel consumed by all phases of combustion and (2) using an estimate of fuel consumed in the flaming zone. Byram's (1959) relationship (3) is graphed for comparison.



Flame residence time was a function of fuel quantity as graphed in Figure 7-14. The poor relationship for headfires reflects the variability of the quantity of fuel consumed in the flaming zone, particularly at high wind speeds, and the difficulty of determining leading and trailing edges of flames. A better relationship was determined for the more stable and well defined backfire flames. Anderson (1964) found that residence time peaked when white pine and ponderosa pine fuels were in the moisture content range of 8-10%, but no such trend was apparent during this study.

Burn-out time, the time taken for all combustion, was also dependent on fuel quantity, although wind speed accounted for 8% of the variation in the case of headfires (Figure 7-15). At low fuel quantities, burn-out time was similar for headfires and backfires. However, heavy and deep fuels continued to smoulder for up to 20 minutes after the passage of backfire flames.

7.4.5 Slope and rate of spread

The effect of slope (S) on rate of spread under zero wind conditions and for uniform jarrah litter fuel is shown in Figure 7-16. Positive slope had a strong positive influence on rate of spread whereas negative slope had a weak but noticeable negative effect. The best equation for predicting rate of spread from slope under these conditions was an exponential of the form;

$r_F = 12.36 * e^{(0.0687*S)}$ (Equation 7-9).

(0.44) (0.068) (parameter standard errors)

Flame angle in relation to the fuel bed (i.e. 90^{o} minus slope) for fires burning on the inclined (sloped) table are graphed in Figure 7-17 along with flame angles of some of the wind driven fires burning on the flat fuel table. The wind driven fires selected from the studies described in section 7.4.2 are those with a fuel quantity and a fuel moisture content similar to the slope experiment fires. It can be seen from Figure 7-17 that the relationship between i) flame angle (slope induced) and rate of spread and ii) flame angle (wind induced) and rate of spread are similar.

Figure 7-14: Flame residence time with the quantity of fuel consumed for backfires and headfires.

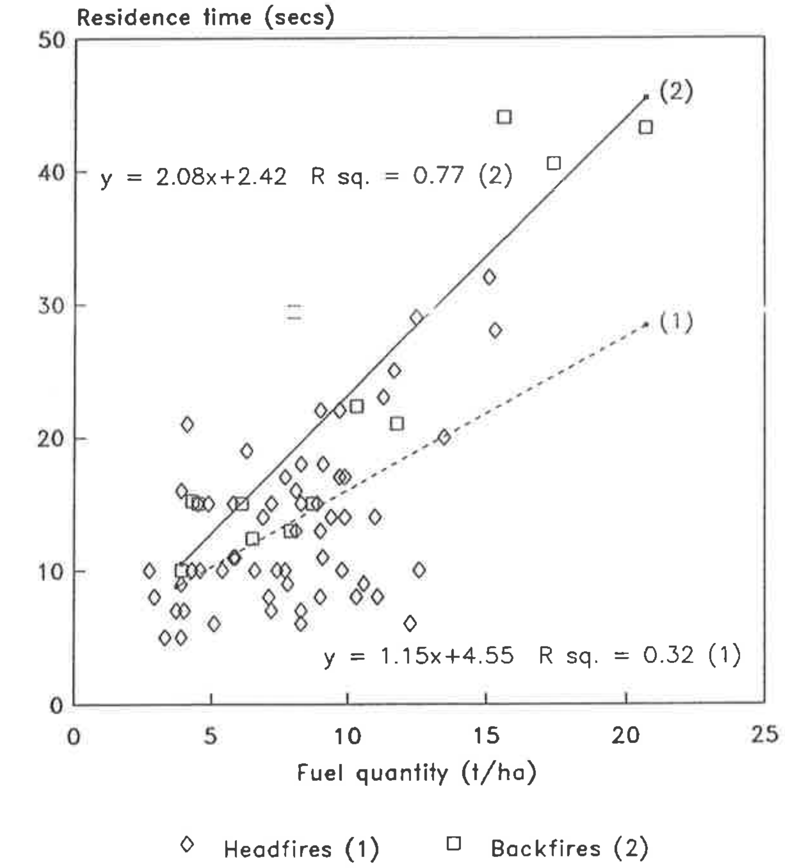


Figure 7-15: Burn-out time with the quantity of fuel consumed for backfires and for headfires. Burn-out time decreased with increasing wind speed (U).

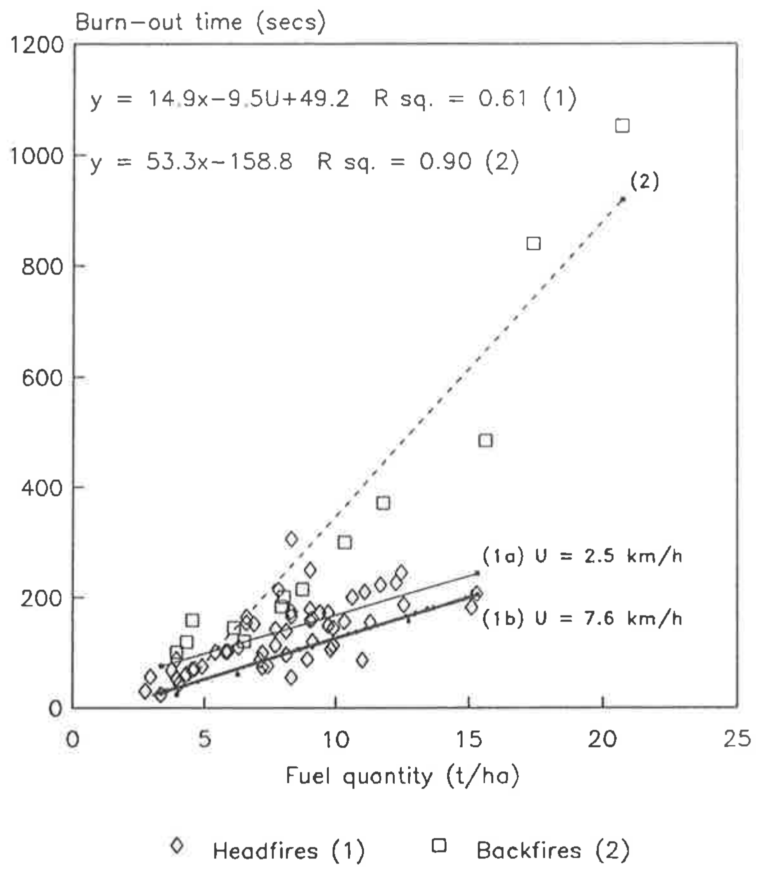


Figure 7-16: The effect of slope on rate of spread (zero wind).

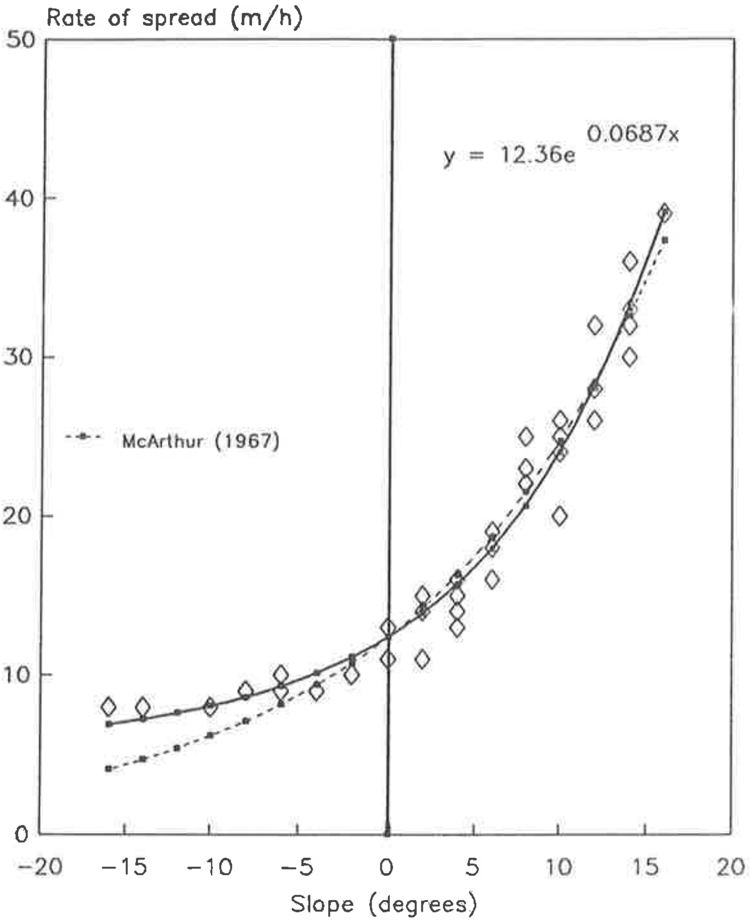
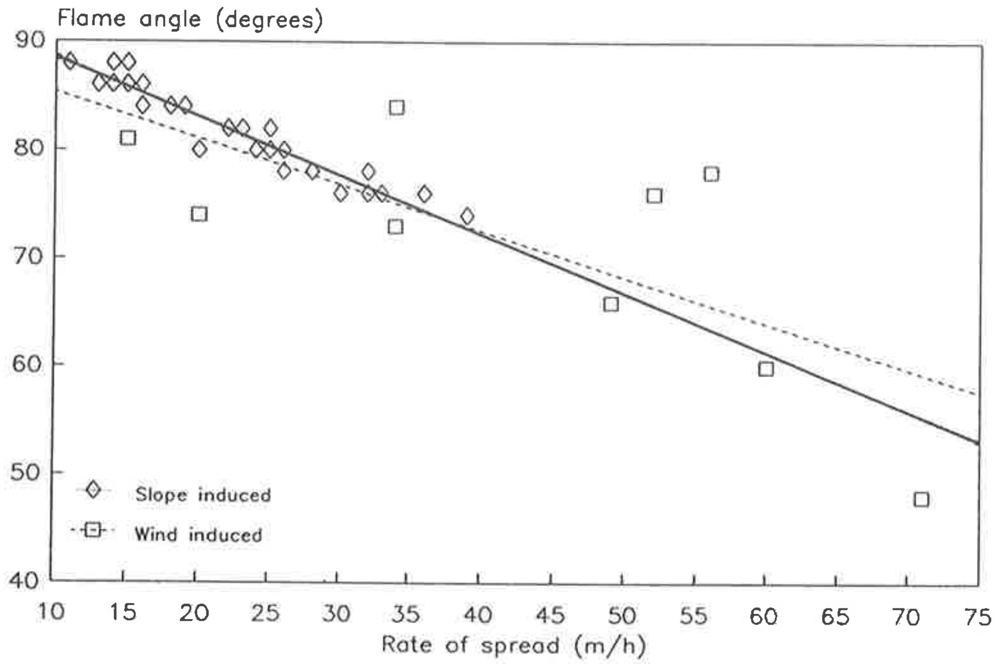


Figure 7-17: The relationship between flame angle and rate of spread is similar for slope-induced flame angle and for wind-induced flame angle.



7.4.6 Wind speed and fire shape

Fires lit from a point source in uniform jarrah litter fuels on the large laboratory table burnt in a roughly elliptical to double ellipse shape under the influence of wind provided by fans. After an extensive examination of fire shape data for a range of fuel types from a range of sources, Alexander (1985) derived a single empirical relationship between fire shape (length-to-width ratio) and wind speed at standard exposure;

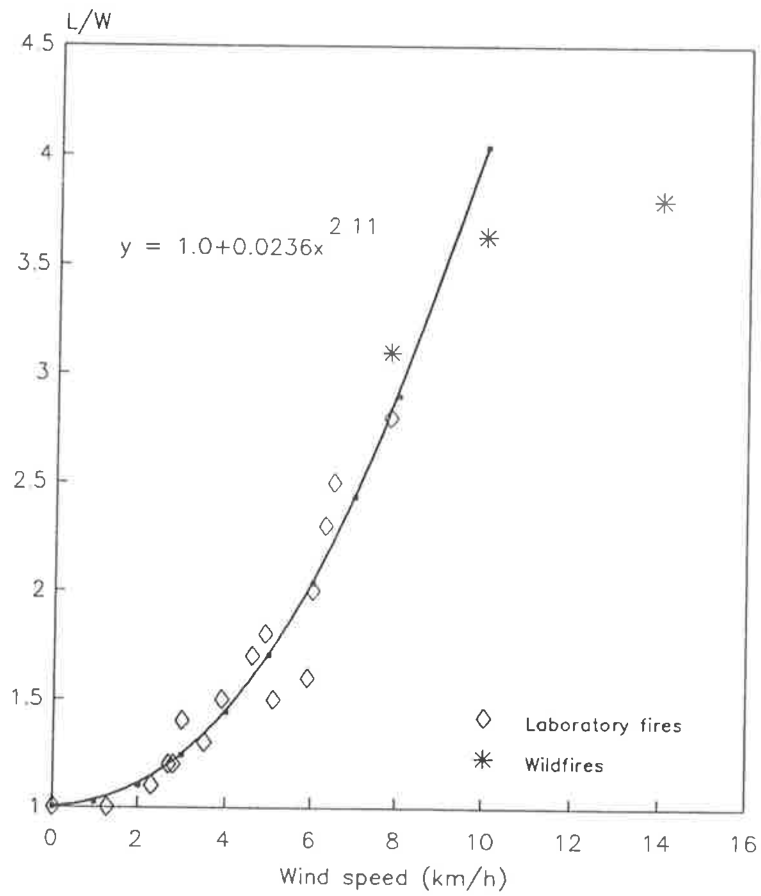
$L/W = 1.0+0.00120*WIND^{2.154}$ (Alexander 1985)

Data obtained by this study were fitted to this equation form and the best fit equation relating fire length-to-width ratio (L/W) and wind speed (U) at 20 cm (0.2 m) above the litter bed was;

$L/W = 1.0+0.0236(U)^{2.114}$.............Equation 7-10
(0.010) (0.247) (parameter standard errors)

Equation 7-10 is graphed in Figure 7-18 along with data from three jarrah forest wildfires (Underwood *et al.* 1985 and McCaw *et al.* 1992). The wildfire data were not used in the regression analysis. Wind speeds for the wildfire data are estimated wind speeds at 1.5 m above the forest floor based on wind reduction models in the FFBT.

Figure 7–18: Fire length-to-width ratio (L/W) as a function of wind speed. Data from three documented wildfires are graphed for comparison with laboratory fires. Wildfire data are from Underwood et al. (1985) and McCaw et al. (1992).



7.5 Discussion

7.5.1 Rate of spread and fuel quantity

Fire behaviour models developed in the field (e.g., McArthur 1962, Sneeuwjagt and Peet 1979, and Forestry Canada 1989) form the basis of forest fire behaviour prediction in Australia and Canada and assume a direct relationship between headfire rate of spread and fuel quantity although there is no reported statistical evidence supporting this relationship. For the experimental fires described by this study, the rate of spread of wind driven fires was found to be independent of the quantity of fuel *per se* on the fire table, but the rate of spread of backfires and zero wind fires was directly related to fuel quantity.

Studies of the effect of fuel quantity on rate of spread are limited and the findings are conflicting. The difficulty of measuring the fuel contributing to the fire spread process probably accounts for this. Fang and Steward (1969) found that fuel quantity had no effect on spread rate in artificial fuel beds. Similarly, Fons (1946) and Fons *et al.* (1962) showed that the rate of spread of laboratory fires was dependent on fuel compactness and fuel density, but was independent of the quantity of fuel per unit area. Steward (1974) reported that rate of spread was independent of "fuel loading density" (fuel quantity) for laboratory fires burning in shredded newspaper and poplar wood shavings and in still air. However, he proposed that this would not be the case for wind driven fires. Carrier *et al.* (1991) theorised that rate of spread was inversely related to rate of spread. This was later demonstrated in the laboratory by (Wolff *et al.* 1991). However, there findings are questionable as fuel quantity was increased by increasing bulk density and packing ratio.

Rothermel (1972) incorporated fuel quantity (loading) in fire spread equations to determine packing ratio and reaction intensity. Reaction intensity and energy release rate (Rothermel and Anderson 1966, Rothermel 1971, Rothermel 1972 and Frandsen and Rothermel 1972) depend on the rate of fuel consumption in the active flaming zone. That is, the fuel contributing to that portion of fire line intensity that is driving the fire. Clearly, fuel loading and fuel contributing to fire spread are different measures for well compacted and relatively coarse fuels such as eucalypt litter. The amount of fuel burning in the flaming zone and the amount of fuel per unit area are similar quantities for fuel arrays which are well aerated and consist of fine particles, such as the artificial cribs etc. studied by Fons *et al.* (1962), Byram *et al.* (1966), Anderson and Rothermel (1965), Thomas (1967), Anderson (1969) and Steward (1971).

A lack of understanding of the fundamental physical and chemical processes of combustion and fire spread limits a theoretical interpretation of the effect of fuel quantity on rate of spread, especially for wind driven fires. There is general agreement in the literature on the way in which fuel properties such as particle size and packing influence rate of spread (e.g., Fons 1946, Beaufait 1965, Anderson *et al.* 1966, Murphy *et al.* 1966, Rothermel and Anderson 1966, Byram *et al.* 1966, Rothermel 1972, Albini 1980, Vines 1981, Albini 1982, Nelson and Adkins 1987, Anderson 1990). However, there is no general agreement on the processes involved. For example, Van Wagner (1967) recognized discrepancies in the mechanisms of heat transfer between laboratory studies using wooden cribs (e.g. Thomas 1965, Byram *et al.* 1966) and those using pine needles (e.g. Beaufait 1965, Rothermel and Anderson 1966). Radiation from flames above the fuel bed was found to be unimportant in the crib studies but appeared to be the main mechanism of fire spread in the needle bed studies. Thomas *et al.* (1961), Fons *et al.* (1962) and Thomas (1970) argued that flames extending above the fuel bed were not sufficiently thick to be very emisive and that heat radiated through the fuel bed was more important. Consequently, rate of spread depended on bulk density and not on the quantity of fuel per unit area (Fons *et al.* 1962). Steward (1971) and Frandsen and Andrews (1979), using a mathematical modelling approach, concluded that convective heating through the depth of the fuel bed was important.

Recently, Cheney (1990b) proposed the concept of fire spreading across the fuel bed surface and down into the fuel bed. Nelson and Adkins (1987) reported that the "key process in the spread of the wildland fuel is horizontal displacement of flame at the fuel surface by a convection mechanism related to wind speed". Interaction between the ambient wind field and flame convection, flame contact, and the concepts proposed by Cheney (1990b) and Nelson and Adkins (1987) helps to explain the behaviour of laboratory fires burning in a jarrah litter fuel bed.

Fires burning under zero wind conditions burnt slowly with erect, stable and discrete flames. Rate of spread was controlled by fuel quantity and moisture content and the flames burnt more or less uniformly through the fuel bed; with radiation within the fuel bed presumably being the primary spread mechanism. The spread ratio (ratio of forward rate of spread-to-vertical (downwards) spread rate) was close to 3. When wind was applied, the flames were tilted, but only tilted significantly to affect rate of spread above a wind speed threshold. This threshold varied between 1-3 km h^{-1} depending on fuel quantity (and probably moisture content but this could not be demonstrated here). At high wind speeds (>3.0 km h^{-1}), flames spread rapidly across the surface of the fuel bed and slowly down into the fuel bed and the spread ratio was high (40-60). Direct flame contact with the fuel bed surface and forced convection of hot and burning gasses through the fuel bed at the combustion interface was the primary mechanism for flame spread which increased linearly with wind speed. With increasing fuel bed depth, hence increased fuel quantity, an increasing proportion of the fuel at depth was consumed in the secondary (flickering) and residual (glowing and smouldering) combustion phases (terminology after Alexander 1982) behind the trailing edge of the flame. Secondary and residual combustion is unlikely to contribute positively to fire spread and theoretically would act to retard spread by shifting the convective centre upwind. In shallow, light fuels (4-5 t ha^{-1}) under high wind speeds (6-8 km h^{-1}), the relatively small flames were blown almost flat onto the fuel bed which was consequently ignited by flame contact. Most of the fuel was consumed in the flaming zone.

The high fire spread ratio (horizontal vs vertical) for wind driven fires reflects the physical nature of jarrah litter fuel beds. In well-aerated fuel beds there is a greater rate of vertical consumption of fuel. Frandsen and Schuette (1978) burning excelsior in the laboratory, clearly demonstrated an inverse relationship between packing ratio and the downward burning rate and reported slow vertical rates of spread and low rates of fuel weight loss for well compacted fuel (i.e. packing ratio = 0.065). Compared with wood cribs and other artificial fuel beds, the leaf litter fuels studied here could be considered as compacted, or poorly aerated, with a packing ratio of 0.06-0.08. Using an equation developed by Rothermel (1972) the optimum packing ratio for the litter fuel studied here is about 0.006. It was very likely that the packing ratio varied through the vertical profile of the fuel bed, increasing with distance downwards from the fuel bed surface. This is the case with field litter beds as described in Chapter 5. The well-compacted nature of jarrah forest litter fuel resulted in a slow rate of vertical or downward consumption of fuel, even though the wind driven flames spread rapidly across the better aerated fuel bed surface. In this laboratory study, forward rate of spread was therefore found to be independent of the quantity of fuel per unit area.

7.5.2 Rate of spread and wind speed

Wind speed has long been proven to be the most important environmental factor affecting fire rate of spread, both in laboratory and field studies (see recent reviews by Beer 1990a, Pitts 1991 and Carrier *et al.* 1991). The precise mechanism of how and why wind speed directly affects rate of spread is not well understood. In general terms, it is probably due to increased oxygenation, better mixing of combustion gasses, increased pre-heating of the fuel bed due to lowering of the flame angle and flame contact with the fuel bed (e.g. Fons 1946, Thomas 1967, Luke and McArthur 1978, Cheney 1981, Chandler *et al.* 1983, Nelson and Adkins 1986).

Wind driven fires in jarrah forests typically progress in surges. This has been observed in other fuel types (e.g., Wade and Ward 1973). Fluctuations in spread rate observed in the field are usually due to i) the gustiness of wind (Albini 1982, Alexander *et al.* 1991) and ii) interaction between ambient wind field and the convection column. In the latter situation, the flames are blown over the unburnt fuel bed, igniting it by direct contact. Fire spreads rapidly across the fuel bed surface (top 10-15 mm) resulting in long, deep flames. A point is reached when the flame is sufficiently deep and the convection energy in the flaming zone is greater than the ambient windfield, and the flames stand nearly vertically. This is characterized by tall, erect and noisy flames which may result in localized crowning and torching. When the fuel bed has burnt down and the convection column loses energy, the wind field again dominates and drives the flames forward.

Fire spread and wind speed data reported by other workers studying both artificial and natural fuel beds in the laboratory have derived either exponential or power equation forms relating rate of spread and wind speed (e.g. Anderson and Rothermel 1965, Byram *et al.* 1966, and review by Pitts 1991). However, Byram *et al.* (1964) reported a linear relationship for wood cribs constructed from 6.4 mm square sticks, suggesting that the form of the relationship is probably a function of fuel particle size.

A feature of the relationship between fire spread and wind speed which lends itself to a nonlinear equation form is the low rate of increase in rate of spread at low (sub-threshold) wind speeds compared with the higher rate of increase at higher wind speeds. Over the range of the experimental data reported by this and other laboratory fire studies, the choice of equation form may not be critical. However, when predicting fire rate of spread beyond this range the equation form will be highly significant. For example, using either linear Equation 2 or non-linear Equation 10 from Table 7-3 above to predict headfire rate of spread over the range of experimental conditions will result in similar predictions. However, for a wind speed of 10 km h^{-1}, the equations predict vastly different rates of spread. Because of a lack of understanding of the fundamental processes of combustion and fire spread, it is difficult to select the equation form which is conceptually correct from experimental data sets which represent a narrow range of potential conditions. However, based on the data presented here, a power equation form best fitted the entire range of wind speeds and a linear form was best for wind speeds >3.0 km h^{-1}.

7.5.3 Rate of spread and fuel moisture content

Fuel moisture content has long been recognized as an important factor affecting ignition and fire spread (Gisborne 1928). The precise nature of the relationship varies from one fuel type to another but the decrease in rate of spread with increased moisture content is conventional wisdom among fire managers and researchers. The physical processes of the influence of moisture on fire spread are reasonably well understood and have been addressed in the literature (for example, Fons 1946, Anderson and Rothermel 1966, Pompe and Vines 1966, Anderson 1969, Davis *et al.* 1959, Brown and Davis 1973, Luke and McArthur 1978, Vines 1981, Gill *et al.* 1981 Chandler *et al.* 1983 and Artsybashev 1984). Albini (1980) has proposed a useful theoretical model which deals with the concept that a limiting value of moisture content can be related to the structural properties of the fuel bed.

Fuel moisture content influences rate of spread and quantity of fuel consumed so affects flame dimensions. Anderson (1964, 1968), studying ponderosa pine and white pine needle beds, showed that flame depth and fuel moisture content were related by a maxima function. Laboratory studies by Rothermel and Anderson (1966) showed that flame depth increased with increasing wind speed but the vertical depth of burn decreased. This was visually apparent here and probably explains why wind speed and not fuel quantity influenced flame depth. The high packing ratio of jarrah litter fuel resulted in slow downward consumption of fuel, so at high wind speeds, combustion rate per unit area (energy release rate) was lower than at low wind speeds, even though the total energy release rate was greater. This phenomenon has been reported by Rothermel and Anderson (1966) for other fuel types studied in the laboratory.

7.5.4 Backfire rate of spread

The backfires studied here were of low intensity (<150 kW m^{-1}), slow spreading and the flames were small and stable, so could be readily studied in the laboratory without concern for scale. Unlike wind-driven fires, there was little or no secondary or residual combustion phases and the compact backfire flames burnt deep into the fuel bed, the entire fuel profile being consumed in the flaming zone.

The benign characteristics of backfires, in terms of control difficulty and potential to cause damage to the natural and built environment, probably explains why relatively little attention has been given to modelling their behaviour. Past studies aimed to assist with the development of mathematical models of fire spread (Thomas *et al.* 1963 and Anderson 1964). However, the backfire is an integral part of the structure, geometry and symmetry of a fire spreading from a point source in a continuous fuel bed, and is the antitheses of the headfire. Fire behaviour changes dramatically around the perimeter of a wind driven fire from the slow, low intensity backfire to the often fast, intense headfire (Catchpole *et al.* 1982 and Catchpole *et al.* 1992). Understanding the processes of backfire spread and the transition in fire behaviour towards the headfire is likely to provide greater understanding of fire spread and fire shape. Backfires are often used to control wildfires (Burrows 1986) and to achieve a range of prescribed burning objectives so an ability to predict the effect of different fuel quantities on backfire behaviour will aid suppression planning and the application of fires for ecological reasons.

Although backfires were slow moving and stable, their spread rate increased linearly with increasing quantity of fuel. This finding is in contrast with headfires reported above. Significantly, flames became deeper, more erect (vertical) and longer with increasing fuel quantity and fuel depth. These relationships also held for fires burning under zero wind conditions, although the zero wind fires spread faster for a given fuel quantity than did backfires burning into wind.

Anderson (1964), working in pine fuels, found that fire rate of spread did not increase when fuel depth exceeded three inches (75 mm). The maximum fuel bed depth studied here was 45 mm, and there was no indication of spread rate saturating. Van Wagner (1967) established a strong curvilinear relationship between backfire rate of spread and fuel moisture content, but suggested that, in theory, fuel quantity should not affect rate of spread. Fang and Steward (1969) reported that the rate of spread of fires burning in wood shavings was unaffected by fuel loading density. Similarly, rates of spread two artificial fuels studied by Steward (1974) were not influenced by fuel quantity or fuel depth. Beaufait (1965) and McAlpine (1988) reported consistent spread rates for backfires in pine needle fuels over a range of wind speeds whereas Murphy *et al.* (1966) found that backfire rate of spread increased with increasing wind speed, although these studies used an artificial non-porous fuel. Ward (1971) found that the rate of spread of backfires burning in *Pinus pinaster* needles was constant, regardless of wind speed and slope (all else being equal).

Assuming backfire rate of spread to be constant or negligible, is common when modelling fire shape (Van Wagner 1969, Potter *et al.* 1979, Anderson 1983, Alexander 1983 and Alexander 1985). This assumption is probably reasonable at high headfire rates of spread, but inaccuracies in modelling fire shape and dimension will become more significant at lower spread rates (Alexander 1985).

The difference between fires burning under zero wind and burning into a constant wind of 4.6 km h^{-1} in this study was the position of the flame in relation to the fuel bed. Under zero wind conditions, the flame was near vertical, but a flame burning into the wind was tilted over the burnt fuel bed. The inverse relationship between flame angle and fuel quantity (when wind speed is constant at 4.6 km h^{-1}) demonstrates the interaction between flame convection and the ambient windfield. At high fuel quantities (>15 t ha^{-1}), flames burning into the wind were nearly vertical. Thus, the wind had little effect on flame attitude when backfires were burning in deep, heavy fuels (fuel depth and fuel quantity were strongly correlated). The point at which a backfire behaves as though it is burning under zero wind (hence likely to spread faster) will depend on the conditions of fuel quantity and ambient wind speed, *ceterus paribus*. For a given wind speed, there is a threshold fuel quantity, below which the windfield will dominate flame convection, causing the flame to tilt over the burnt fuel bed. This threshold obviously increases with increasing wind speed. Other factors (held constant during backfires studied here) such as fuel moisture content and slope probably influence this relationship.

Rothermel and Anderson (1966) developed mathematical models explaining flame tilt as a function of the relative magnitude of the fire and wind forces. The magnitude of fire forces was found to be a function of the combustion rate per unit area of fire. If this is large then the flames will not be tilted and rate of spread will be low. Rothermel and Anderson (1966) found that the energy release rate was dependent on wind speed, such that low or no wind resulted in high energy release per unit area of burning fuel. Therefore, flames are more erect and rate of spread is low. This theory helps to explain the behaviour of backfires studied here. The energy release rate of a fire burning into wind was a function of the fuel quantity. Vertical depth of burn (into the fuel bed) increases with decreasing wind speed (Rothermel and Anderson 1966), so is probably near maximum for fires burning in zero wind and for backfires. Therefore, increasing fuel quantity produced a higher energy release rate per unit area of combustion and more erect, taller flames.

In this study, the length and depth of backfire flames related well to the rate of fire spread in jarrah litter fuel and supports findings in other fuel types (Byram *et al.* 1966, Rothermel and Anderson 1966, McArthur and Cheney 1966, Thomas 1967 and McArthur 1968a). Radiation flux from a flame is a function of its size (Anderson 1968 and Packham and Pompe 1971). Backfires burning in jarrah leaf litter produced relatively small flames which leant away from the unburnt fuel bed. Thermocouple traces showed that the temperature of thermocouples on the fuel bed surface ahead of the advancing flames did not rise significantly until the flames were very close.

This is consistent with other findings (Rothermel and Anderson 1966, Fang and Steward 1969 and Frandsen 1973) and with the conclusion that relatively low level radiation is the primary source of heat transfer to unburnt fuel during backfires, which therefore spread very slowly. Interestingly, the relationship between pre-heat distance and fuel quantity (therefore rate of spread) saturated at a fuel quantity of about 12 t ha^{-1}. This is approaching the quantity at which flames tended to 90^{o}.

7.5.5 Headfire flame dimensions

Flame size was a function of wind speed, (or rate of spread) and fuel quantity, or more precisely, the quantity of fuel involved in the combustion zone. Rate of spread and flame depth were independent of fuel quantity and were largely dependent on wind speed. This evidence suggests that increasing flame size is primarily an effect of increasing rate of spread and not a cause. That is, large flames and associated radiation output are a consequence of fast spreading fires and of more fuel being consumed, not the cause. Wind forced the flames through and across the fuel bed, involving more fuel in the combustion zone and generating larger flames and higher intensities. Increased radiation falling on the fuel bed surface will obviously lead to more rapid pre-heating. When flames were erect (near 90^{o}), that is, when the convection column dominated the wind field, fires spread very slowly. The wind speed necessary to tilt the flames over the fuel bed increased with fuel quantity (Figure 7-11) as convection energy is directly related to the quantity of fuel being consumed in the flaming zone (Byram 1959). There was no significant increase in rate of spread until flames were tilted more acutely than about 80^{o} which required a wind speed of 2-4 km h^{-1} depending on fuel quantity (Figure 7-11).

7.5.6 Fire Intensity

Using w_C (Method 1 above) to calculate intensity resulted in very high values for a given flame length compared with using C_{CZ} (Method 2 above), which produced values similar to Byram (1959) (Figure 7-13). Method 1 assumes that all heat is released in the flaming zone, which was clearly not the case. This is consistent with the discussion above and with Cheney's (1990b) fire spread concept that not all fuel contributes equally to the intensity of a wind driven fire. The difficulty of accurately determining fuel consumed in the flaming zone severely limits the usefulness of intensity as a universal descriptor of fire behaviour. Simply measuring the total quantity of fine fuel burnt and using this to calculate fire intensity results in an over-estimate of fire intensity because a significant and variable (and difficult to measure) proportion of the fuel is burnt behind the flaming zone. The magnitude of over-estimation should be constant for a given fuel type so relationships between intensity and fire behaviour or impact will be meaningful for that fuel type. Cheney (1991) showed that it was inappropriate to compare and characterise fires burning in different fuel types using intensity alone. Calculating fuel consumed in the flaming zone, as described in section 7.4.3, and using this to calculate intensity above provides a more meaningful estimate of intensity but is cumbersome and depends on knowing flame depth and residence time.

For a given fuel complex, flame size is the ultimate measure of energy output so alternatively, fire intensity can be estimated from flame length. For jarrah forest fires in predominantly litter bed fuels Equation 7-8 relating fire intensity and flame length should be used to estimate fire intensity. Flame length can be predicted from Equation 7-3 but the relationships between flame dimensions and fire intensity reported in this study apply only to fuel beds with similar characteristics to those for which the relationships were developed.

7.5.7 Rate of spread and slope

The relationship between rate of spread and slope (Equation 7-9) is similar to the equation developed by Noble *et al.* (1980) using data taken from McArthur's fire behaviour meters (McArthur 1966, 1967a and 1973). Van Wagner (1977) compared data on the effect of slope on rate of spread from five published sources and found that all were reasonably similar. He derived an upslope equation from a subjective average line drawn through data from the five sources but cautioned that relationships derived in the laboratory may not be valid in the field due to differences of scale. The behaviour of fire burning upslope is strongly affected by the degree of slope whereas fire burning downhill is less sensitive to slope (Equation 7-9, McArthur 1967a and Van Wagner 1977). Some fire behaviour models (e.g, Rothermel 1972), assume that fires burning downhill behave as if on level terrain, but as noted by Van Wagner (1988) it is important to understand how negative slope affects rate of spread for accurate fire growth modelling. Van Wagner (1988) reported that spread rate decreased with increasing negative slope by 64% for a slope of -22° which is similar to the findings reported here. On the other hand, Ward (1971), working with maritime pine (*Pinus pinaster*) litter bed fuel in the laboratory, found that rate of spread downslope was constant, regardless of the degree of negative slope.

As with other studies, the slope - rate of spread experiments reported here were conducted in the absence of wind. Where wind and slope are aligned, the FFBT and the McArthur Forest Fire Danger Meter assume the effects to be additive, but there are no procedures for determining rate of spread when slope and wind are not aligned. Other models (e.g., Rothermel 1972 and 1983) determine the resultant of two spread vectors; one for slope (zero wind) and one for wind. Albini

(1976a) vectorised slope only and used the vector aligned with wind to correct rate of spread. The shortcomings of these approaches have been reviewed by McAlpine *et al.* (1991) who have proposed a new procedure for resolving slope - wind interactions. They present a model which converts slope to an equivalent wind speed, which is then used in vector analysis with actual wind speed to determine rate of spread. The relationship between flame angle and rate of spread graphed in Figure 7-17 held regardless of whether flame angle was wind induced or slope induced. Slope has a similar effect on fire spread as wind in that it changes flame angle with respect to the fuel bed. This finding supports the notion of treating slope as an equivalent wind speed. The model proposed by McAlpine *et al.* (1991) has therefore been modified and adopted for use in jarrah fuels, as described in Chapter 13.

7.5.8 Fire shape and wind speed

An ability to predict fire shape has important ramifications for planning both wildfire suppression strategies and prescribed burns. For a given fuel, the rate of growth and the shape of a spreading fire is largely a function of wind speed, providing direction is constant and the terrain uniform (see Anderson 1983, Alexander 1985). Under these conditions, fires burning in more or less continuous fuels will eventually burn in an approximately elliptical shape (e.g. Curry and Fons 1938, Fons 1946, McArthur 1966, Van Wagner 1969, Anderson *et al.* 1982). The shape of an ellipse can be conveniently expressed by its length-to-width ratio, as used by Pirsko (1961), McArthur (1966) and Cheney (1981). A comprehensive review of ellipse properties in relation to fire spread has been prepared by Alexander (1985). Equation 7-10 relates fire shape in the laboratory with wind speed at 20 cm above the fuel bed. Alexander's (1985) equation was derived from field data and uses a standard exposure wind speed (at 10 m in clear air). Therefore, it is difficult to make direct comparisons, but a comparison of regression coefficients reveals that Equation 7-10, developed here, is not as curved as Alexander's (1985) equation.

There is ample experimental and anecdotal evidence demonstrating the acceleration of fire spread from a point source (e.g Peet 1967a, McArthur 1967a, Cheney and Barry 1969 and McAlpine 1988). The rate of "distortion" of fire shape, from an initial circular shape to the final elliptical shape, under the influence of wind has been reported by McAlpine (1988, 1989), studying laboratory fires and Weber (1989a, 1989b) has made useful advances in the understanding and modelling of fire acceleration from a point source. The relationship between fire shape and wind speed graphed in Figure 7-18 assumes that a steady state was reached. The limited field data for jarrah fires (Figure 7-18) suggests that the relationship developed from small scale laboratory studies holds reasonably well for the field situation. This is surprising as field observations indicate that rate of spread could take from 10-70 minutes to stabilize. It is possible then, that final fire shape stabilizes relatively quickly, even though fires may still be accelerating.

Peet (1967) developed a linear relationship between the rate of spread of flank fires and head fires for small, mild fires burning in jarrah forest litter fuels. In the field, the fires burnt in an ovoid shape. Peet (1967) reported that, up to a head fire rate of spread of about 80 m h^{-1} (4 feet min^{-1}), the L/W ratio did not exceed about 1.30 (measured from Figure 4, Peet 1967). As no wind data were provided by Peet, it is not possible to make direct comparisons with the laboratory results reported here. Green *et al.* (1983) tested the adequacy of several geometric shapes, including elliptical, double elliptical, ovoid shapes and even rectangles, and found that all provided good approximations to actual fire shapes. They concluded that little gain could be made by attempting to fit complicated shape models to fire spread patterns. Green (1983) reported that, while an ellipse was adequate for modelling shape in continuous fuels, it was not adequate for patchy fuels. Fires burning in patchy hummock grasslands fuels had little or no back and flank fire development and burnt in straight lines or "fingers" (Burrows *et al.* 1991).

7.6 Concluding discussion

Fire behaviour in eucalypt fuels has been traditionally studied in the field. These studies represent the first attempt at examining the behaviour of eucalypt litter fires in the partially controlled laboratory environment. Laboratory studies are limited by the scale of the fires and by the extent to which conditions of fuel and wind in the laboratory reflect those in the real world. However, important relationships were studied and described with a degree of control which is impossible to achieve in the field. Important findings emerging from these laboratory experiments in relation to the behaviour of fire in jarrah litter are:

i) Even under partially controlled laboratory conditions, combustion and fire spread are highly sensitive and highly variable phenomena.

ii) Rate of spread of wind driven fires was independent of fuel quantity and most variation was explained by wind speed and fuel moisture content. However, backfire rate of spread was directly related to fuel quantity such that doubling fuel quantity caused a doubling of rate of spread.

iii) At wind speeds below about 3 km h^{-1}, flames were near vertical and fires spread slowly depending on fuel quantity. Above this speed, flames were tilted and fires spread rapidly across the fuel bed surface and slowly down through the fuel bed. Flame size was determined by rate of spread and fuel quantity. Flame contact appeared to be the primary spread mechanism.

iv) Over the entire range of wind speeds (0.0-7.6 km h^{-1}), the best equation form relating wind speed and rate of spread was a power function. For wind speeds above 3 km h^{-1}, the best form was a linear one.

v) The quantity of fuel consumed in the flaming zone of fires fanned by strong winds was not equal to fuel quantity per unit area and was impossible to measure, making precise calculation of fire intensity impossible.

vi) Headfires would not spread when fuel moisture content exceeded 21% odw and when fuel quantity was less than about 3.5 t ha^{-1}.

vii) The effect of slope on rate of spread was similar to that reported by other workers. Slope affects rate of spread in a similar manner to wind speed, by changing the orientation of the flames.

viii) The relationship between fire shape and wind speed developed in the laboratory appears to hold for field conditions. This is tested in the following chapter (Chapter 8).

ix) In reviewing wind-aided fire spread theory, Carrier *et al.* (1991) cite a number of authors who emphasised the long length of fire run required to achieve a steady state of faster spreading fires in the laboratory. It is highly likely that the faster spreading laboratory fires reported here (wind speed = 7.6 km h^{-1}) had not reached a steady state, highlighting a serious limitation of the laboratory for studying fire behaviour. The larger scale field experiments reported in Chapter 8 provide an opportunity to test the fire behaviour models developed from these laboratory studies and to compare the two techniques for predicting fire behaviour.

CHAPTER 8

FIRE BEHAVIOUR EXPERIMENTS IN THE FIELD

8.1 Introduction

An ability to accurately forecast fire danger and to predict fire behaviour is fundamental to sound fire management of the jarrah forest. Forest fire behaviour modelling in Western Australia has evolved over several decades, as described in Chapter 3. Prior to the studies described by this thesis, the 1979 edition of the Forest Fire Behaviour Tables for Western Australia (FFBT) (Sneeuwjagt and Peet 1979) formed the basis for modern jarrah forest fire behaviour prediction. The FFBT were based on Peet's (1965, 1972) pioneering fire behaviour research.

Peet's (1972) point ignition fire experiments were "primarily aimed at improving the techniques for fire suppression and controlled burning". His original research was conducted in small plots (<0.2 ha), restricting full fire development, and under relatively mild conditions. The limitations of the fire behaviour model developed from these studies are discussed in Chapter 4. The need to conduct further fire behaviour experiments arose out of new developments in jarrah forest fire management, including higher expectations and standards of wildfire control and increasingly sophisticated applications for prescribed burning (see Chapters 1 and 3). There was some concern among fire managers and researchers that the existing model (Sneeuwjagt and Peet 1979) under-estimated fire rate of spread under dry fuel conditions (Peet pers. comm.). Wildfires burning under dry conditions were observed to spread significantly faster than predicted.

As well as a need to be able to forecast fire danger and accurately predict the spread of wildfires, fire managers need reliable fire behaviour models to safely implement prescribed burns over a wide range of fuel and weather conditions to achieve the objectives described in Chapter 1. Prescribed burning under warm, dry conditions in summer or early autumn to regenerate or eradicate specific plant species or to control insect pests by fully scorching the tree canopy, is risky. Fire behaviour can quickly escalate, resulting in uncontrolled, intense fires (e.g Burrows 1984). Wildfires caused by lightning or arsonists are, by and large, outside the control of fire management agencies, but escapes from prescribed burns are undesirable both in terms of costs and public credibility. Therefore, it is vital that fire behaviour models are reliable over the range of prescribed burning conditions and that model users are aware of model assumptions and limitations.

The experiments described in this chapter aimed to accomplish the following objectives:

i) Examine and model the behaviour of quasi steady state (line ignition) fires over a wide range of fuel and weather conditions in a standard jarrah forest litter fuel. Rate of spread under these conditions represents the jarrah fire danger index (FDI) which is the basis for predicting forest fire danger and fire behaviour in all except karri forest fuel types in Western Australian forests.

ii) Compare the fire spread model developed from the laboratory experiments (Chapter 7) with observations of field fire behaviour.

iii) Compare fire rates of spread observed in the field with those predicted using a) the 1979 version of FFBT (Sneeuwjagt and Peet 1979), which was developed from Peet's (1972) experiments, b) McArthur's Forest Fire Meter and c) Rothermel's (1972) laboratory model.

Fire behaviour data used in this study were from a number of sources, as described in Table 8-1. The majority of experimental fires were conducted in Young and Harrington State forests in the south-west of Western Australia over the warm, dry summer months (January-March) of 1979 and 1980 (see Table 8-1 and Figure 8-1). The experiments were conducted during the Prohibited Burning Period, when the Bush Fires Act normally prohibits the lighting of fires. A suspension of the Act was obtained to conduct these experiments, but under the conditions of the suspension, no fires could be lit when the Forest Fire Danger Rating for the region exceeded HIGH or when the Minister decreed a total fire ban. Additional fire behaviour data were gathered during the burning of fire ecology experimental sites (Boundary, Perup and McCorkhill), and from a few operational low intensity prescribed burns throughout the jarrah forest. Data from a single, well documented fast spreading wildfire which burnt in Andrew State forest west of Manjimup was also included in the data set (McCaw *et al.* 1992). Although some 300 wildfires occur in the south-west each year, the technical documentation of these fires is generally too poor for use in analysis for fire modelling. Sources of fire behaviour data are summarised in Table 8-1.

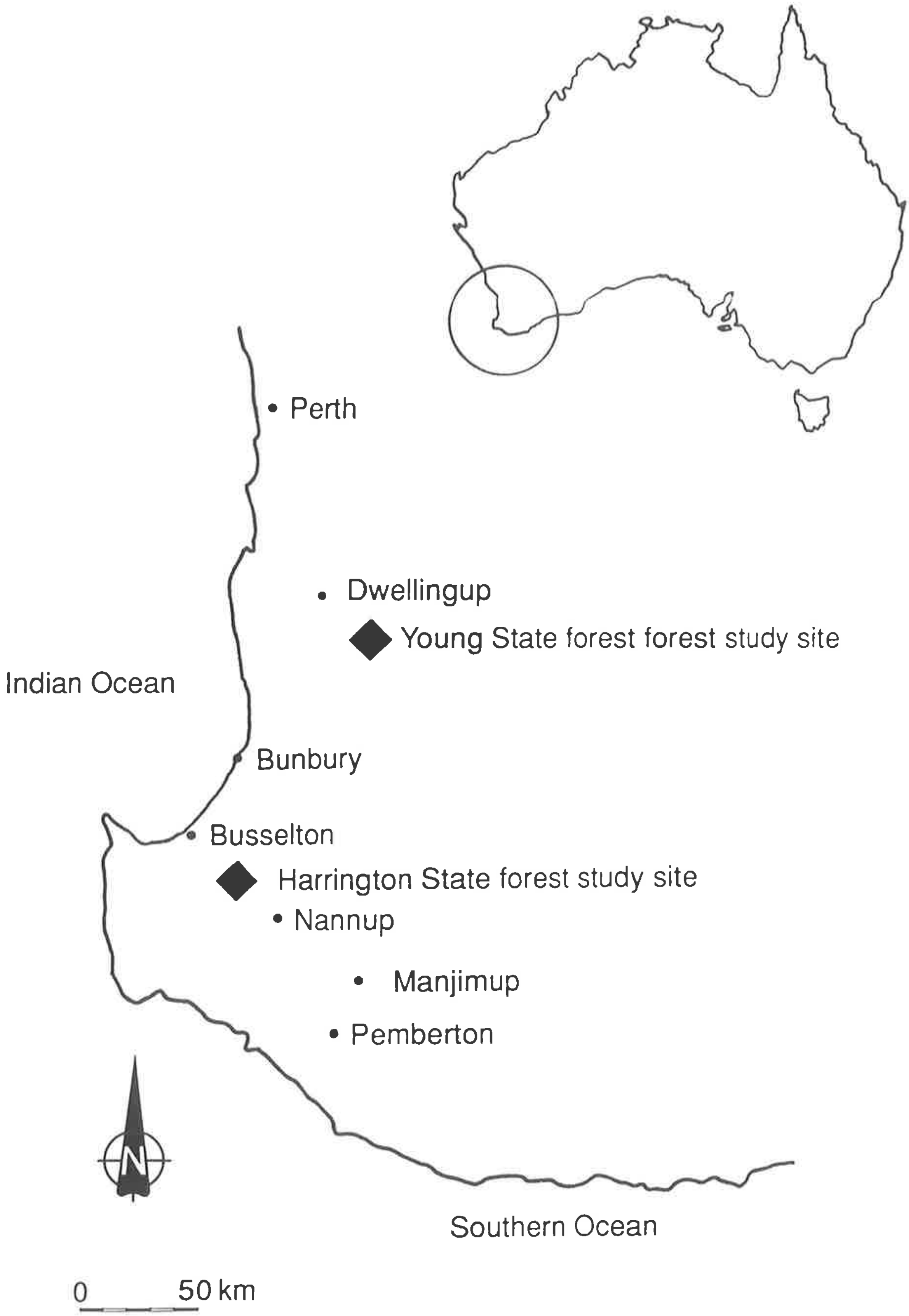


Figure 8-1: Location of jarrah forest fire behaviour experiments in the south-west of Western Australia.

Table 8-1: Summary of data sources used in analysis of fire behaviour in jarrah forests.

Location (forest block)	Year burnt	Number of plots	Plot size (ha)	Fuel age (years)
Harrington	1979	23	2.0	7
Young	1980	17	2.0	7
Perup	1987-92	6	4.0	4,5
McCorkhill	1988-91	10	4.0	3,5,7
Boundary	1989-90	4	1.0	4,5
Operational fuel reduction		6	2.0	5,7
Andrew	1991 wildfire		(McCaw *et al.* 1992)	3

8.2 Methods

The research methods adopted in this study were similar to those used by most workers studying fire behaviour in the field (e.g., McArthur 1959, Peet 1972, Stocks and Alexander 1980, Stocks 1987 and Alexander *et al.* 1988.). Significantly, plots were considerably larger than those studied by McArthur (1959) and Peet (1972) and most fires (57 of 67 plots) were ignited by a line of fire rather than a point source. Experiments were conducted in standard jarrah forest fuel types on flat or gently sloping terrain in plateau jarrah forest (described in Chapter 5) so that findings would be compatible with the FFBT and with earlier work by McArthur (1959) and Peet (1972). Importantly, the jarrah FDI is equivalent to headfire rate of spread under these "standard" fuel and topographical conditions (Sneeuwjagt and Peet 1976 and 1979).

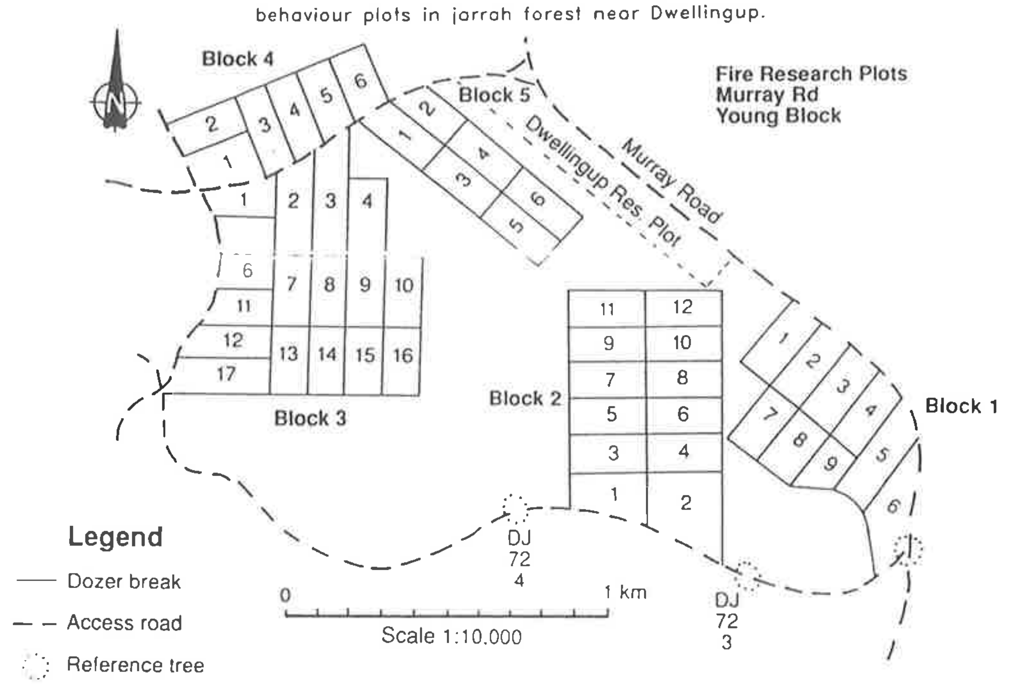
8.2.1 Site description - Young and Harrington State forests

The Dwellingup study site was located in Young State forest, 25 km south-east of Dwellingup (Figures 8-1 and 8-2). The area experiences a Mediterranean type climate, with warm to hot dry summers and cool wet winters with an average annual rainfall of about 1,000 mm. In this dry sclerophyll forest, jarrah and marri form the overstorey species with jarrah making up about 70% of the total tree basal area. The mean top height was about 25 m, mean tree basal area was about 26 m^2 ha^{-1}, and overstorey canopy cover varied from 40-70%. Most (85%) trees were less than 40 cm in diameter measured at breast height and over bark (dbhob). The lower tree stratum (up to 7 m above the ground) comprised mainly of jarrah saplings, *Banksia grandis, Allocasuarina fraseriana* and *Persoonia longifolia*. The low, sparse understorey (mean height 0.3 m, projected ground cover <10%) consisted of species such as *Adenanthos barbigera, Macrozamia riedlei, Hovea chorizemifolia, Leucopogon verticillatus, Xanthorrhoea gracilis, Hibbertia* *amplexicaulis, Lasiopetalum floribundum, Dryanda nivea, Loxocarya flexuosa, Acacia strigosa, Styphelia tenuiflora* and *Patersonia rudis*. A continuous ground cover of fine litter (leaves, twigs and floral parts) formed the dominant fuel. The photograph (Plate 8-1) typifies the Young forest study site.

Young State forest was selectively logged in the 1930s and regular (5-7 years) low intensity (<350 kW m^{-1}) fuel reduction burns were carried out there since the mid 1950s. The study area was last burnt in spring 1973 by low intensity fire for fuel reduction so fuels were 7 years old at the time of experimentation. Forest surrounding the study site was burnt in 1979 as part of the then Forests Department's (now Department of Conservation and Land Management) fuel reduction program.

Plate 8-1: Young State forest near Dwellingup, W.A. Typically, upland jarrah forest has a low, open and sparse understorey.

Figure 8-2: Location and layout of experimental fire behaviour plots in jarrah forest near Dwellingup.



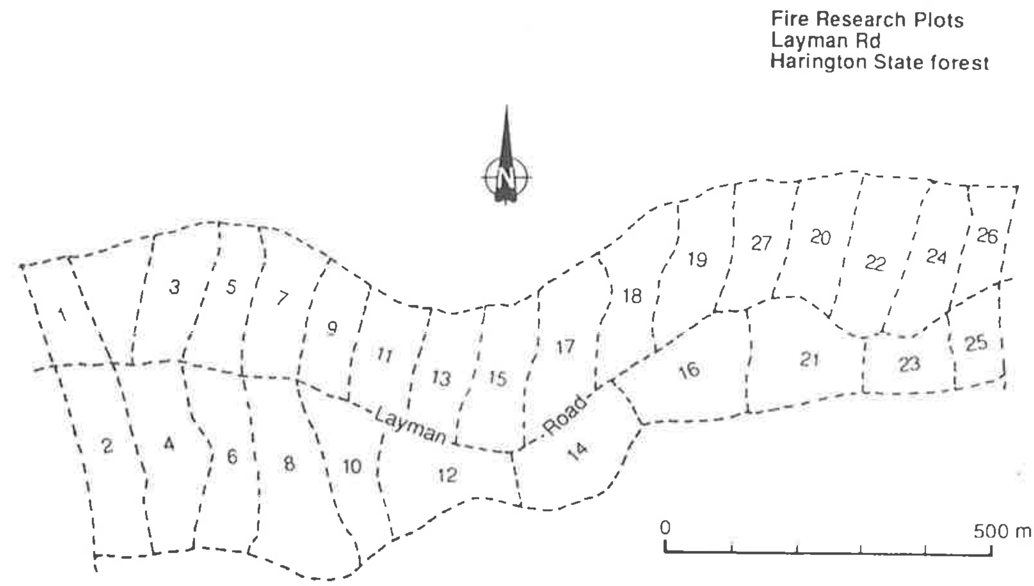


Figure 8-3: Location and layout of experimental fire behaviour plots in jarrah forest near Kirup.

The second study site of 80 ha was located 7 km east of Jarrahwood in Harrington State forest within the Donnybrook Sunkland (Figures 8-1 and 8-3). The geology and geomorphology of the region have been described in detail by several authors (Prider 1966, Finkl 1971, McCutcheon 1978, 1980 and Churchward and Dimmock 1989). Climate is similar to that experienced at the Young site.

The fuels and vegetation of the Harrington site were similar in structure to the standard northern jarrah forest, although there was a higher understorey scrub component. The vegetation was an open forest, similar to the Young forest site but with a lower mean top height (20-25 m) reflecting the poorer quality of this forest. Jarrah and marri formed the overstorey with a projected crown cover of 30-60%. Jarrah formed the dominant tree species. Lower trees (up to 6 m) consisted of scattered *Banksia grandis, Allocasuarina fraseriana*, and *Persoonia longifolia*. Understorey vegetation was somewhat more continuous than the Young forest site, with a projected ground cover of 20-35%. Common understorey species were *Acacia browniana, Acacia pulchella, Adenanthos barbigera, Adenanthos obovata, Agonis parviceps, Burtonia villosa, Hakea lissocarpa, Hibbertia hypericoides, Leucopogon glabellus, Leucopogon verticillata,* and *Pultanea reticulata*. Understorey height varied from 0.2-1.5 m, averaging about 0.6 m. Plate 8-2 typifies this site.

At both sites, a rubber-tyred tractor was used to construct 100 m x 200 m experimental burn plots, each separated by a 3 m wide mineral earth break. Plot layout for both sites is shown in Figures 8-2 and 8-3. A 20 m x 20 m grid was permanently marked in each plot using 2.0 m pegs. Grid positions formed the basis for sampling fuels, fire behaviour and scorch height.

8.2.2 Perup, McCorkhill and Boundary sites.

These sites were established to study the long term effects of various fire regimes on the jarrah forest and provided an opportunity for gathering additional fire behaviour data. The McCorkhill State forest site, some 25 km west of Nannup, is climatically, structurally, and floristically similar to Harrington. The Perup site, about 40 km east of Manjimup, is in the low rainfall forest zone (750 mm annum^{-1}) so the trees are shorter (15-20 m) and the understorey lower and more open than higher rainfall forests to the west. Understorey vegetation was low (< 0.5 m) and sparse (<15% cover) and litter formed the dominant fuel. The fuels at this site were structurally similar to the Young State forest. The Boundary site was located in high rainfall mixed jarrah forest about 10 km west of Manjimup.

Plate 8-2: The Harrington State forest fire behaviour experiment site north-west of Nannup, W.A.

Plate 8-3: Standard jarrah forest fuel. Note surface litter, coarse woody material, live and dead aerated scrub.

Plate 8-4: Measuring the depth of surface litter fuel which is dominant fuel in standard jarrah forest fuel.

Plate 8-5: A fire fighter mopping up after an experimental fire.

Plate 8-6: Surface litter fuels are completely burnt under dry summer conditions. Note the white ash residue after the combustion of coarse woody material.

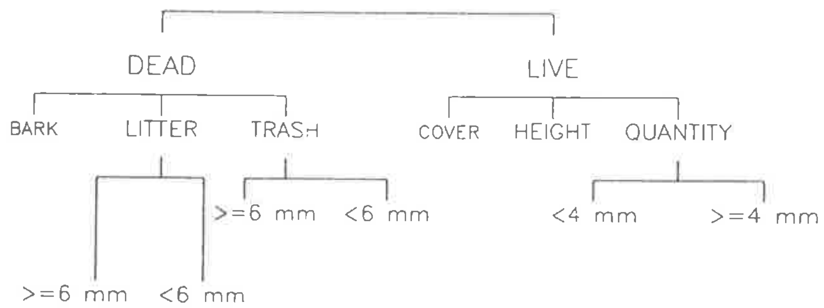
The 200 m x 200 m experimental fire plots varied in fuel quantity but were mostly 5-7 years since last fire, which is a relatively narrow age range (Table 8-1). Variation in fuel quantity provided an opportunity to examine the effect of this parameter on rate of spread. The plots were burnt under milder weather conditions than the Harrington and Young plots so spread rates were generally less than 100 m h^{-1}. Ignition was by way of a line of fire of varying length (100 to 150 m). Fire behaviour observations were made over 15-60 minute intervals but the fires were not mapped.

8.2.3 Fuel quantity and structure

A detailed description of a standard jarrah forest fuel is presented in Chapter 5. During this study, all live and dead vegetation from the soil surface to a height of 2 m was classified according to Figure 8-4 and measured. Vegetation above 2 m was too sparse to warrant inclusion as fuel. The sparsely foliaged tree crowns were 10-15 m above the litter bed and the horizontal distance between tree crowns, while variable, was mostly 5-10 m.

The quantity of litter fuel (< 6 mm in diameter) in each plot was measured by determining the mean depth of the litter bed within each grid cell and using the relationship between litter bed depth and quantity described in Chapter 5. Ten fuel depth measurements were made (one every 2 m) along 20 m transect lines between each grid position using a Sneeuwjagt litter depth gauge. Each grid cell (20 m x 4 m) was then assigned a litter quantity on the basis of this sampling (e.g., Figure 8-5).

Figure 8-4: Classification of jarrah forest fuels.



During the laboratory fire behaviour experiments described in Chapter 7, the quantity of fuel placed on the fire table was variable between fires, but was constant across the table for each fire. In the field, however, fuel quantity was variable within and between plots (e.g., see Figure 8-5). Therefore, determining the quantity of fuel influencing the behaviour of the field fires was not straight forward. Three methods for determining rate of spread and the quantity of fuel involved in fire spread were tested to examine the effect of fuel quantity on headfire rate of spread.

i) The mean fuel quantity for each plot was analysed with the mean headfire rate of spread through the entire plot (plot fuel quantity).

ii) Headfire rate of spread was determined every 15-20 minutes as the crescent-shaped fire front spread through the plot. The mean of fuel cells through which the apex of the headfire spread during each spread interval was determined and used in analysis (apex fuel quantity).

iii) As for ii) above except that the mean of all fuel cells within the headfire crescent burnt out during a spread interval was determined and used in analysis (crescent fuel quantity).

The three methods described above are illustrated in Figure 8-5.

The quantity of large, dead, woody material (>6 mm in diameter) lying on the forest floor was measured before and after burning along the same transects (Figure 8-5) and using a line intercept technique (Van Wagner 1968b). All material intercepted was tallied into 25 mm diameter size classes and the quantity of fuel in each class was calculated using the class mid-point diameter and expressed in t ha^{-1}.

Understorey vegetation (scrub fuel) within each fuel sample cell (20 m x 4 m) was first typed and mapped according to species assemblages using techniques described by Havel (1975) and McCutcheon (1980). Three vegetation types, or pyro-botanical types, were identified based on biomass and cover and are summarised in Table 8-2. Biomass (oven dry) samples were harvested from a number of 1 m^2 quadrats located in each type and a point sample technique (Levy and Madden 1933) used to determine mean height and cover (Table 8-2).

Table 8-2: Havel (1975) site types (pyro-botanical types) and associated fuel characteristics. Standard errors in parentheses.

	Pyro-botanical Type (codes)		
	T	CD	G
Number of biomass samples	30	39	52
Mean biomass (t ha^{-1})	0.6 (0.04)	5.2 (0.31)	2.4 (0.18)
Mean height (m)	0.28 (0.02)	0.84 (0.12)	0.41 (0.03)
Mean cover (%)	6 (0.44)	54 (6.1)	33 (4.2)
Coverage over study site (%)	44.1	14.5	41.4

The incorporation of bark as fuel in eucalypt forests is often overlooked. Peet and McCormick (1965b) reported that up to 9.7 t ha^{-1} of bark was burnt from standing trees during high intensity fires in well stocked, high quality jarrah forests near Dwellingup in 1961. Ward *et al.* (1985 unpubl.) working in jarrah forests similar to those reported here determined a relationship between height of bole char and quantity of bark burnt for marri and jarrah trees. For a forest with a tree basal area of about 25-30 m^2 ha^{-1}, the quantity of bark burnt during moderate to intense fires under dry conditions (outer bark moisture content 4-6% of odw.) was about 4.5-5.5 t ha^{-1} (Ward *et al.* 1985 unpubl.).

8.2.4 Weather observations

Weather records were divided into historical (pre-fire) weather and weather experienced during the experimental fires. Pre-fire weather records were obtained from the nearest permanent weather stations at Dwellingup and Kirup for Young and Harrington forests respectively. Weather recorded at these centres included daily rainfall, continuous temperature and relative humidity traces, dew point, and wind speed and direction at two hourly intervals (during working hours; 0800-1700 western standard time (WST)) at standard exposure (10 m into clear air) (Department of Science, Bureau of Meteorology Manual 1977). Historical weather records were primarily used to maintain the Soil Dryness Index (SDI) (Mount 1972, Burrows 1985), which is a measure of the seasonal dryness of soil, vegetation, deep forest litter fuels and logs lying on the forest floor.

During the experimental fires, a portable weather station was located on site. This consisted of i) two sensitive cup (50 mm) analog type mechanical anemometers, one set at 1.5 m and one at 10 m above the forest floor, ii) a thermohydrograph and an aspirated physchrometer set at 1.5 m above the forest floor. The weather station was set in unburnt forest about 50 m from the plot to be burnt at right angles to the prevailing wind direction.

Figure 8–5: An example of the grid layout within 100 m x 200 m fire behaviour plots. Fuel sample cells are continuous 20 m x 4 m quadrats. The mean litter fuel quantity (t/ha) within each cell is shown. Three methods were used to analyse the effect of fuel quantity (fuel Q) on rate of spread, as described in the figure. Fires were ignited by a line of fire at the ORIGIN.

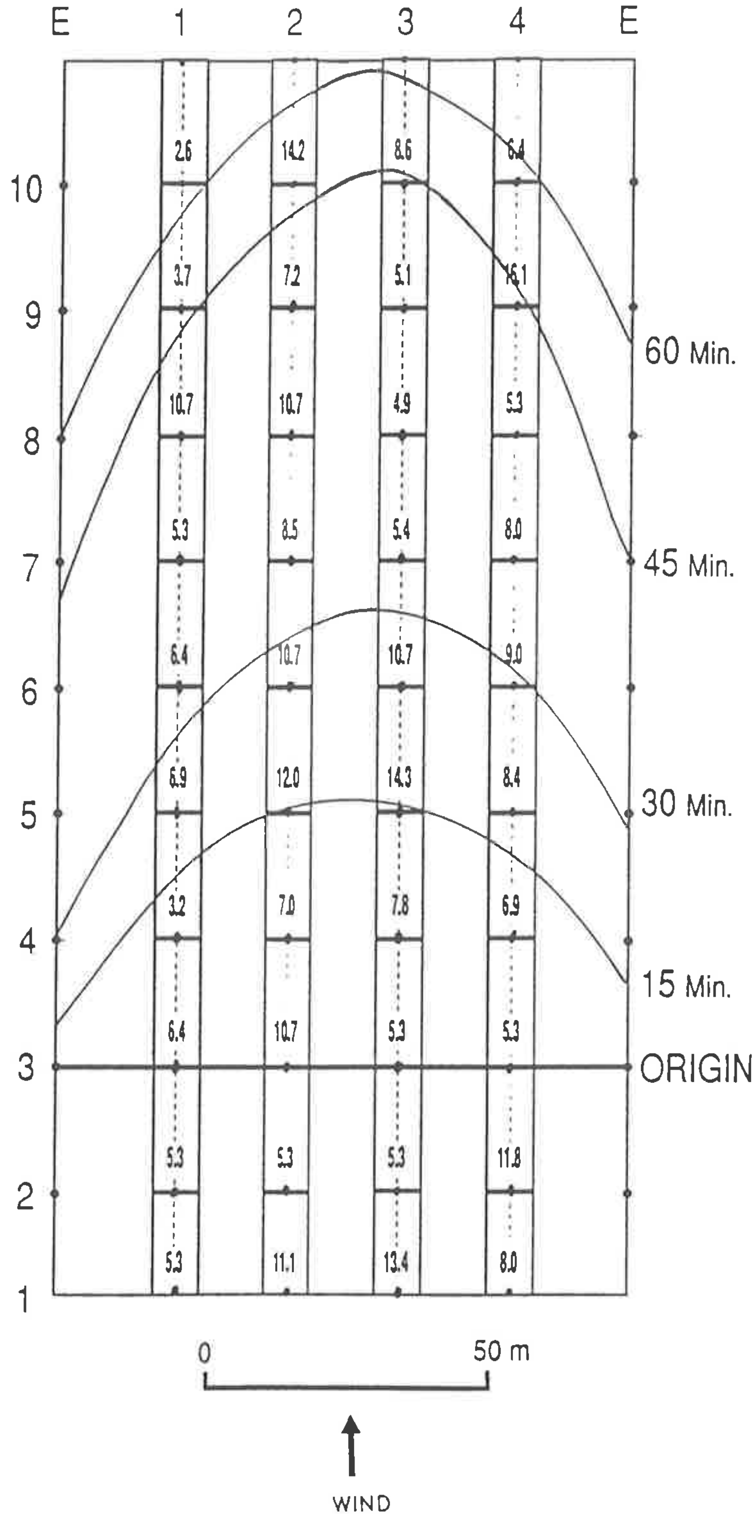
Method1:
Mean head fire rate of spread and fuel quantity for entire plot.
$\bar{x}$ ROS = 160mh-1
$\bar{x}$ Fuel quantity = 8.1

Method 2:
Sampling ROS at 15 minute intervals, averaging fuel quantity along apex of head fire
i.e.

Interval	ROS	Fuel Q
0 -15	168	6.5
15 - 30	128	12.5
30 - 45	292	6.52
45 - 60	72	8.6

Method 3:
Sampling ROS at 15 minute intervals, averaging fuel quantity in burnt crescent
i.e.

Interval	ROS	Fuel Q
0 - 15	168	6.6
15 - 30	128	9.3
30 - 45	292	7.5
45 - 60	72	9.8



Legend

- plot boundary
- Fuel cell
- pegged grid position
- fire position
- fuel transect line

An observer recorded wind run and direction at 1.5 m and 10 m above the forest floor over five minute intervals for the duration of each fire. Wind speed and direction varied during the burning of each plot so for the various time periods over which spread rates were averaged, the resultant wind vector was determined by plotting the five minute interval wind runs (distance and direction). The resultant vector (distance) was then divided by the time over which the rate of spread was determined and used in subsequent analysis. Winds experienced at the Young site were mostly light and variable south-easterlies, whereas winds at the Harrington site were generally stronger and less variable westerly sea breezes. As well as a continuous thermohydrograph trace, ambient wet and dry bulb temperatures were recorded at the start and finish of each fire.

Plate 8-5: A mechanical weather station consisting of a sensitive cup anemometer at 10 m (not shown), an anemometer at 1.5 m and an aspirated psychrometer.

8.2.5 Fuel moisture content

The Soil Dryness Index (SDI) (Mount 1972, Burrows 1987b) was maintained to provide a measure of the seasonal dryness of soils, vegetation and coarse fuels, as described above. At the time of igniting each plot and at hourly intervals thereafter, the moisture content of the litter fuel was determined from six samples, each of about 50 g, from the top 10-15 mm of the litter bed (surface moisture content or SMC as defined by Sneeuwjagt and Peet 1979, 1985) and six of the entire litter profile down to mineral earth (profile moisture content or PMC). Previous tests had shown that six samples provided a reliable estimate of fuel moisture in the plot, with a standard error of less than 4% of the mean. During dry summer conditions, the moisture content of litter bed fuels is controlled by atmospheric humidity and temperature (Luke and McArthur 1978 and Sneeuwjagt and Peet 1979), resulting in a high degree of spatial uniformity across a level experimental plot of 1-2 ha. Samples were taken throughout the plot from areas in mottled shade at the time of sampling and placed in air tight containers. At a later date, samples were dried in a conventional oven for 48 hours at 105^{o} C and moisture content calculated as per cent of oven dry weight (odw).

Initially, the leaf and fine twig (< 4 mm in diameter) moisture content of live vegetation up to 2 m was sampled daily at noon, but this was abandoned for several reasons. Firstly, there was considerable variation both between and within plant species, depending on where the sample was taken. Secondly, there was no significant diurnal trend in moisture content, even allowing for variation. Instead, live vegetation was sampled weekly during the study to monitor long term trends. This was achieved by harvesting 15, 50 g samples each of leaf and of green stem (< 4 mm diameter) material and drying it as described above for litter fuels.

The weekly moisture content of dead, coarse woody fuels lying on the forest floor was represented by extracting 10 core samples to a depth of 100 mm from a log 300 mm in diameter. In the absence of significant rain, log moisture content varied only slightly during this study. The moisture content of outer (dead) and inner (live) bark of jarrah and banksia trees was also sampled weekly.

8.2.6 Fire Behaviour

Gill and Knight (1991) have emphasised the importance of accurate fire measurement in order to develop accurate fire models. They also acknowledge the difficulties of obtaining accurate measurements in the field. Fire behaviour characteristics (linear rates of spread, fire area and fire perimeter) of point source fires have usually been measured in the field by some method of tagging the fire perimeter at regular time intervals (e.g. McArthur 1962, Peet 1965, Cheney 1971 and Alexander *et al.* 1988). Another technique which has been used successfully is sequential remote sensing using oblique or aerial photography, video and infra-red imagery, either from a mobile platform such as a fixed wing aircraft, or a stationary platform, such as a tower or helicopter (Packham and McArthur 1966, Cheney *et al.* 1968, Johns 1986, Adkins and Rodgers 1986, Mak and Hutchins 1987 and Alexander *et al.* 1988, Cheney *et al.* 1989). In some instances, fire spread has been determined by recording the time at which the flames reach a fixed point in a pre-determined grid or some referenced position (e.g Woolliscroft 1968, 1969, Alexander *et al.* 1988). A variation on this technique involves using thermocouples or electronic timers with fusible links set on a grid to record the arrival of flames (Blank and Simard 1983).

Whatever the technique, fire rate of spread is the easiest fire behaviour variable to measure. However, the turbulent and dynamic nature of fast spreading flames makes flame dimensions difficult to measure accurately in all but the mildest of bushfires. Flames are normally described according to height, length, depth and angle, as defined by Byram (1959), Rothermel and Deeming (1980), Cheney (1981) and Alexander (1982). In the field, flame dimensions are commonly estimated visually, often against a calibrated scale of some type. Various forms of imagery such as photographic and video, have also been used to measure flame dimensions (Alexander *et al.* 1988). Ryan (1981) described a method for estimating flame height using a cotton string soaked in fire retardant.

Ultimately, the technique used to measure fire behaviour depends on the needs and circumstances of each situation. Here, aerial photography or video recording of fires was unsuitable because smoke and vegetation would quickly obscure the flames. Infra-red technology was beyond the capacity of this project and probably not warranted given the size of the plots. Tagging the fire perimeter at regular intervals is a sound technique when it is safe to do so, but is inaccurate, dangerous or impossible during periods of intense fire behaviour.

Jarrah forest fire danger rating and fire behaviour predictions are based on headfire rate of spread in standard fuel on level terrain. Headfire is the most active in terms of spread rate, intensity and flame dimensions so is of greatest concern to fire managers. The steady build-up and acceleration of fires ignited from a point source is a well documented phenomenon (McArthur 1967a, Luke and McArthur 1976, Cheney 1981 and McAlpine 1988), although none of the present models have been tested in jarrah forest fuels over the range of potential burning conditions. Weber (1989a) has advanced an understanding of the build-up phenomenon, through a physical model which identifies the curvature of the fire front as the entity that drives fire acceleration. Depending on fuel and surface burning conditions, fires originating from a point source can take several hours and develop to a considerable size before reaching a "quasi steady state" (Cheney 1981). Even under mild conditions, Peet (1962 unpubl.) showed that fires lit from a point source took 20-30 minutes to reach a steady rate of spread of 40-60 m h^{-1}.

The primary aim of this experiment was to model steady state headfire spread rate in standard jarrah fuel. To reduce the build-up time of the experimental fires in the 2 ha plots used here, 57 of the 67 plots were ignited by a 100-150 m line of fire set along the up-wind edge of each plot. Usually, the fire was allowed to burn for 20-40 m before monitoring commenced. Based on current understanding of fire build-up (e.g. Cheney 1981, Weber 1989a and Cheney *et al.* 1993), line ignition reduces the build-up time considerably, allowing fires to reach a steady state relatively quickly. Ignition time was recorded and fire rate of spread was measured by observers who walked parallel to the flames, down each side firebreak and recorded the time flames reached each peg on the grid system. The position of the flames in relation to the grid positions was also mapped at 5 minute intervals.

Normal procedures for executing a burning program under suspension of the Bush Fires Act were followed. Forests Department (now CALM) suppression crews from Dwellingup and Nannup contained the fires and mopped up after each plot was burnt.

When flames reached each grid position, visual estimates of mean flame height, length and depth were made. Flame height was the vertical distance from the leading tip of the flame to the fuel bed, flame length was the distance from the tip of the flame to mid-way along the base of the flame. Flame depth was the horizontal distance from the base of the leading edge of the flame to the base of the trailing edge of the flame. It was difficult to decide exactly where the trailing edge of the flames was, particularly for fast moving fires. Flame dimensions of fast moving, unstable fires proved very difficult to estimate accurately in the field. Difficulties in obtaining accurate and precise measures of flame dimensions in the field have also been reported by Johnson (1983). The three observers assisting with these experiments were experienced fire researchers and made similar estimates of flame size. The 2 m high pegs marking the grid positions were also used as height references, which assisted observations. Opportunistic observations of spotting, smoke colour and unusual fire behaviour such as torching, were also made.

Byram's fire intensity (Byram 1959) was calculated for each observation period (20-100 m of fire run; see data analysis section below) using the average headfire spread rate over that period (distance fire travelled/time), the average quantity of fuel consumed and a heat yield of 18,700 kJ kg^{-1} (dry) adjusted for fuel moisture content (Alexander 1982). The quantity of fuel consumed in the flaming zone was estimated in the field by sampling fine fuel (< 6 mm diameter dead, < 4 mm live) quantity before and after the fire, as described above. It was assumed that all material in these size classes was in fact consumed in the flaming zone. Depth of burn, a commonly used measure in Canada (Stocks 1987, Stocks 1989) was not measured in this study as the dry conditions resulted in almost total combustion of the litter profile down to mineral earth over most of the plots. The contribution of coarse (>= 6 mm diameter) fuels (logs etc.) to flaming zone combustion was calculated using the rate of weight loss relationships developed in Section 4. Bark loss, measured as described above, was included in the intensity calculation. A high proportion (up to 90% based on observations of bark burn-out time) of all bark combustion on the lower portion of the tree boles occurred during the residence time of surface flames, therefore within the flaming zone. Bark loss was calculated from bole char height measurements and then using the relationship reported by Ward *et al.* (1985 unpubl.).

Several weeks after the experimental fires, average canopy scorch height was assessed between each grid position using a calibrated stick for heights up to 2 m and a clinometer for scorch above 2 m.

8.2.7 Data Analysis

Two fire behaviour data sets were generated. Firstly, up to five headfire rate of spread observations were extracted at different times and from a single fire in each plot as the line fires progressed through the plot. Selection was based on wind alignment to ensure that only headfire runs were included in analysis. Careful selection of observations by excluding those which were affected by wind shifts removed a significant amount of variability in rate of spread due to changes in wind direction. However, this process risked violating normality assumptions because multiple observations from the same fire were not necessarily independent. For line ignition fires, the minimum time interval for an observation used in the data set was 15 minutes. Point ignition fires were allowed to burn for 45-120 minutes before headfire spread rates were used in the analysis. Fuel moisture and weather conditions (wind speed, temperature and relative humidity) were averaged over the same time period for regression with mean rate of spread for that period. This data set was used to model fire behaviour.

In addition to multiple observations from the same fire, the average rate of spread for the entire fire (plot) was also determined for each plot. These data were analysed separately to examine the effect of fuel quantity on headfire rate of spread.

Data analysis and the headfire rate of spread model building procedure followed along the lines of that described for the laboratory studies (Chapter 7). A Pearson correlation coefficient matrix was generated to screen for those variables important in affecting headfire rate of spread and for those which were not. Important variables were then plotted against rate of spread to provide a graphical view of the form of the relationship. Linear and nonlinear least squares fitting procedures (SAS Institute Inc. 1985 and Meyers 1989) were employed to formulate regression models to estimate functional relationships describing the data. Meyers (1989) is of the opinion that simplifying regression analysis by performing transformations alters the error structure and risks violating either the homogeneous variance assumption or the normality assumption. A disadvantages of nonlinear regression analysis is that confidence intervals and prediction intervals are very difficult to determine (Meyers 1989). Criteria used to choose the best prediction model were (after Myers 1990):

i) Coefficient of determination (R^2 for linear regression and S, goodness of fit, for nonlinear regression).
ii) Estimate of error variance or residual mean squares (s^2).
iii) Bias and precision, as defined in Chapter 7.
iv) Analysis of residuals.

Where several models could be fitted to the data with nearly equal effectiveness against the above criteria, then final model selection was based on a judgement of which was most suitable for predicting fire behaviour for applied fire management, the primary aim of this study.

Actual rates of spread and model predictions developed from these field experiments were compared with;

i) the model developed from laboratory studies,
ii) predictions made using the 1979 edition of FFBT (Sneeuwjagt and Peet 1979),
iii) McArthur's (1965) Forest Fire Meter,
iv) Rothermel's (1972) model.

Predictions using the 1979 version of the FFBT were made using the standard procedure of working through the various tables and interpolating between rate of spread classes. Actual field observations of wind speed, fuel moisture content and fuel quantity were used.

8.3 Results and Discussion

Statistics describing the variable ranges and variation during these field experiments are shown in Table 8-3. Generally, weather conditions over the duration of the study were warm, dry and stable. The SDI for the Young and Harrington experimental series is graphed in Figure 8-6. Experimental fires were not permitted by law on days of VERY HIGH or EXTREME fire danger, thereby excluding the opportunity to study fires burning under unstable and severe weather conditions. The maximum headfire spread rate recorded during the experimental fires was 660 m h^{-1}, with most fires spreading less than 150 m h^{-1}. Data from a well documented wildfire (McCaw *et al.* 1993) burning in upland jarrah forest with a headfire rate of spread of 1,000 m h^{-1} were included in the analysis.

Due to the dry conditions under which most of the experimental fires burnt (SDI > 1200), litter fuel was completely consumed down to mineral earth. The proportion of coarse fuels which burnt varied but generally increased with fire intensity and SDI. Aerial fuel, consisting primarily of live scrub, was low and sparse. Under these conditions, the crowns of mid and upper strata trees were not incorporated as fuel, although there was occasional and localized "torching" or flame extension through to the upper canopy. There was considerable crown fire development during the wildfire reported by McCaw *et al.* (1993). The quantity and particle size of scrub fuel which burnt varied considerably. Generally, all live leaf and twig material up to 2 mm in diameter was consumed by low intensity fires (<500 kW m^{-1}), with material up to 4 mm being consumed by higher intensity fires. Aerial fuel did not contribute noticeably to fire rate of spread.

Table 8-3: Descriptive statistics for fuel, weather, and fire behaviour variables measured from 206 observations made during fire behaviour studies in jarrah forest litter fuels in which 67 plots were burnt. Pearson correlation coefficients (R_C) of variables with headfire rate of spread are also shown.

Variable	Range	Median	Mode	R_C
Litter fuel < 6 mm (t ha^{-1})	3.2-19.5	8	10	-0.16
Coarse fuel >= 6 mm (t ha^{-1})	0.0-128.2	-	-	-
Litter fuel moisture (% odw)	3.0-18.6	6.6	6	-0.41
Ambient temperature (^{o}C)	15-43	27	30	0.56
Relative humidity (%)	15-68	39	42	-0.38
Wind speed (1.5 m) (km h^{-1})	1.6-8.8	3.9	3.4	0.77
Wind speed (10 m) (km h^{-1})	2.6-12.0	5.6	5.0	0.76
Headfire rate of spread (m h^{-1})	12-1,000	73	30	-
Headfire flame height (m)	0.1-6.6	1.4	0.5	0.89
Headfire flame length (m)	0.1-10.0	1.8	2.0	0.90
Headfire intensity (kW m^{-1})	37-4,368	355	86	-

Plate 8-8: A line ignition fire progressing through a 2 ha experimental plot near Dwellingup. Flames are momentarily erect during a lull in wind speed.

Plate 8-9: Early stages of a point ignition fire. Fires ignited this way were allowed to burn for 45-120 minutes before rate of spread data were used in analysis.

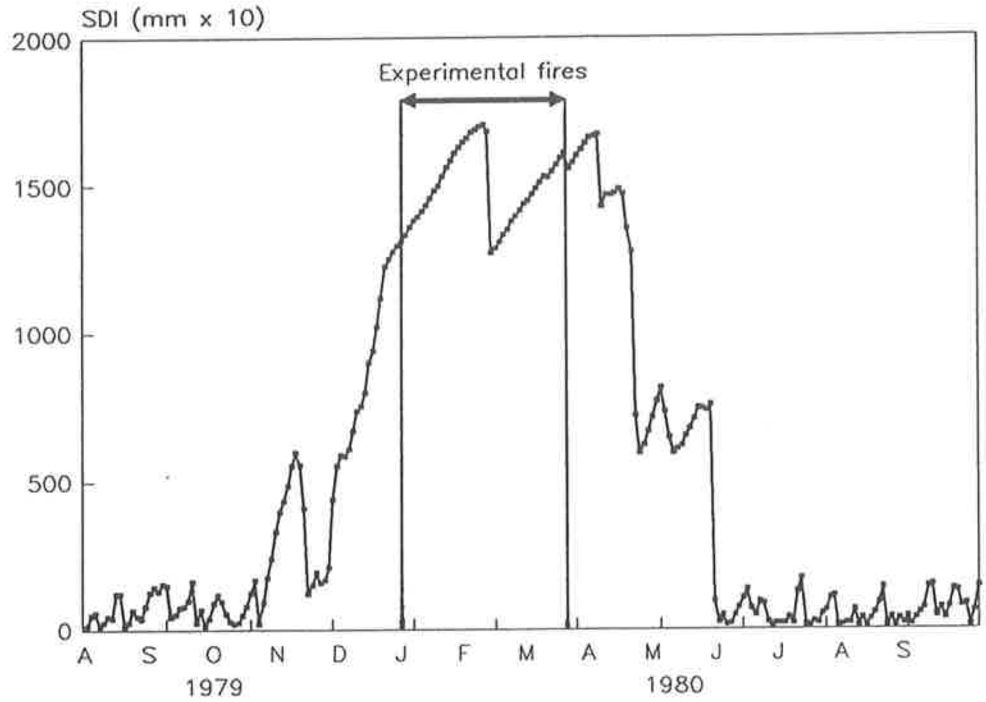
Plate 8-10: A low intensity, slow spreading fire burning in dry fuels under the influence of light winds (< 3.5 km h^{-1}).

Plate 8-11: A headfire spreading at about 150 m h^{-1} with 1.5 m high flames. Notice flame extention by combustion of live vegetation.

Plate 8-12: A high intensity experimental fire. Rate of spread is about 600 mh^{-1}.
(Photo G. Cutting).

Plate 8-13: Under warm, dry conditions, bark on standing trees ignites readily and makes a significant contribution to the energy output of a fire as well as generating fire brands.

Figure 8–6: Soil Dryness Index (SDI) calculated at Dwellingup.



8.3.1 Modelling headfire rate of spread

Pearson correlation coefficients for primary dependent and independent variables are shown in Table 8-3. Headfire rate of spread is strongly dependent on wind speed, weakly dependent on fuel moisture content and independent of fuel quantity. The effect of fuel quantity on headfire rate of spread is analysed further (see below) using the whole plot data set, as described in Section 8.2.7 above.

Headfire rate of spread is graphed with wind speed for all fires in Figure 8-7. Laboratory fire data (from Chapter 7) are graphed for comparison. The limitations imposed by scale in attempting to develop fire rate of spread prediction models from the laboratory experiments are evident in Figure 8-7. The relationship between the rate of spread of laboratory fires and wind speed is linear above a wind speed of about 3.5 km h^{-1} (Chapter 7), whereas the field data show a nonlinear relationship. Clearly, laboratory fires burning under the influence of strong winds had not reached a steady state and spread rates were significantly lower than field fires experiencing similar wind speeds (Figure 8-7).

The importance of wind speed on headfire rate of spread has been widely reported in the literature for a range of fuel types, both natural and artificial, and is reported in Chapter 7 above. On many occasions during these field experiments wind speeds were < 3.5 km h^{-1}, resulting in low, erect, stable and slow spreading fires (see Plate 8-10). When the wind speed was sufficiently high to tilt the flames over the fuel bed, then fires spread rapidly; strong wind gusts blew the flames down onto the fuel bed causing very rapid fire spread (see Plate 8-11). Observations made during the course of the experiments suggest that there are wind speed thresholds which must be exceeded before flames are tilted sufficiently over the fuel resulting in headfires developing and rapid fire spread. While the threshold appeared to vary inversely with fuel moisture content and directly with fuel quantity, wind speeds exceeding about 3.0-3.5 km h^{-1} were necessary before there were any indications of strong headfire development. This threshold windspeed range is similar to that reported for the laboratory studies (Chapter 7). While a definitive threshold relationship could not be described from the field data, this phenomenon is reflected in the form of the equations in Table 8-3 which are graphed in Figure 8-8. Beer (1991) showed that the effect of wind speed on headfire rate of spread also depended on atmospheric stability, with fires spreading faster under unstable conditions. Atmospheric stability was not measured during these experiments so its effects on headfire rate of spread could not be determined.

Headfire rate of spread was graphed with wind speed by fuel moisture content classes to determine the best form of the relationship between the two variables, as shown in Figure 8-8. There were insufficient data for fuel moisture content classes above 12% to warrant graphing. Statistical criteria for model comparisons are presented in Table 8-4.

Based on the statistical criteria presented in Table 8-4, the power equation form is better than the exponential at predicting headfire rate of spread, with both non-linear forms being superior to the linear form. The power functions under-predict slightly at very low wind speeds, but more importantly, the exponential forms make unrealistically high predictions on extrapolation to high wind speeds. While there are no sound data to confirm headfire rates of spread at high wind speeds and under dry fuel conditions, casual observations of wildfires suggests that the spread rates predicted by the exponential form seriously over predict across the full range of potential fire conditions likely to be experienced in jarrah forests, and particularly at high wind speeds.

Table 8-4: Summary of statistics for comparing candidate models for predicting headfire rate of spread (r_F) from wind speed (U) by fuel moisture classes (SMC). The equations are graphed in Figure 8-8. Linear models apply for U > 3.5 km h^{-1}.

Equation r_F =	S	s^2	Residuals Range	Residuals Mean	Precision	Bias
			3% < SMC <= 4%			
$25.88e^{0.494U}$	0.97	2349	-66.6-74.8	-5.8	15.3	-7.5
$3.78U^{2.78}$ - 9.23	0.98	748	-49.0-37.2	0.5	19.1	3.1
220.3U - 730.3	0.96	2679	-87.1-59.2	-1.9	41.4	13.9
			4% < SMC <= 6%			
$20.97e^{0.42U}$	0.82	1984	-77.2-213.3	-1.1	28.9	-4.6
$5.84U^{2.04}$ - 10.1	0.83	1841	-76.1-199.0	0.6	26.1	0.2
66.35U-171.9	0.81	1998	-81.7-187.0	0.0	39.9	7.5
			6% < SMC <= 8%			
$13.65e^{0.45U}$	0.88	955	-69.6-166.2	-1.3	29.7	-9.4
$1.65U^{2.63}$ + 4.56	0.91	723	-66.0-140.7	1.3	31.7	2.5
68.65U - 206.8	0.79	1772	-86.0-154.5	0.7	35.5	8.2
			8% < SMC <= 12%			
$6.80e^{0.45U}$	0.85	82	-12.2-17.0	0.6	28.6	0.1
$2.29U^{2.09}$ + 2.1	0.87	78	-10.8-19.6	0.4	30.4	1.6
22.78U - 43.86	0.84	85	-11.3-22.3	0.0	42.4	5.3

Figure 8–7: Headfire rate of spread with wind speed for experimental fires in the field and in the laboratory.

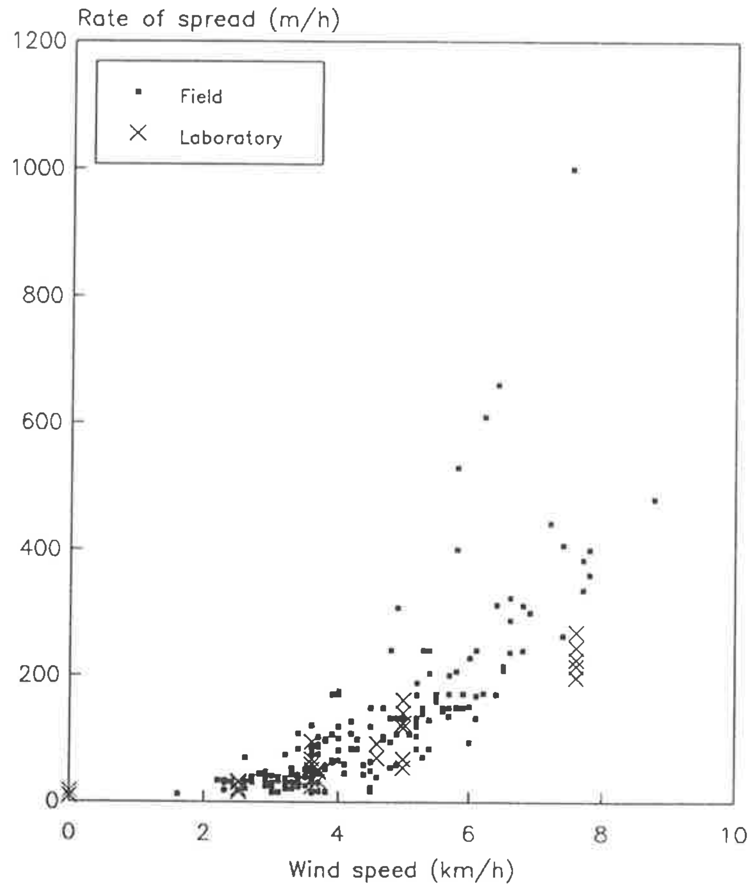
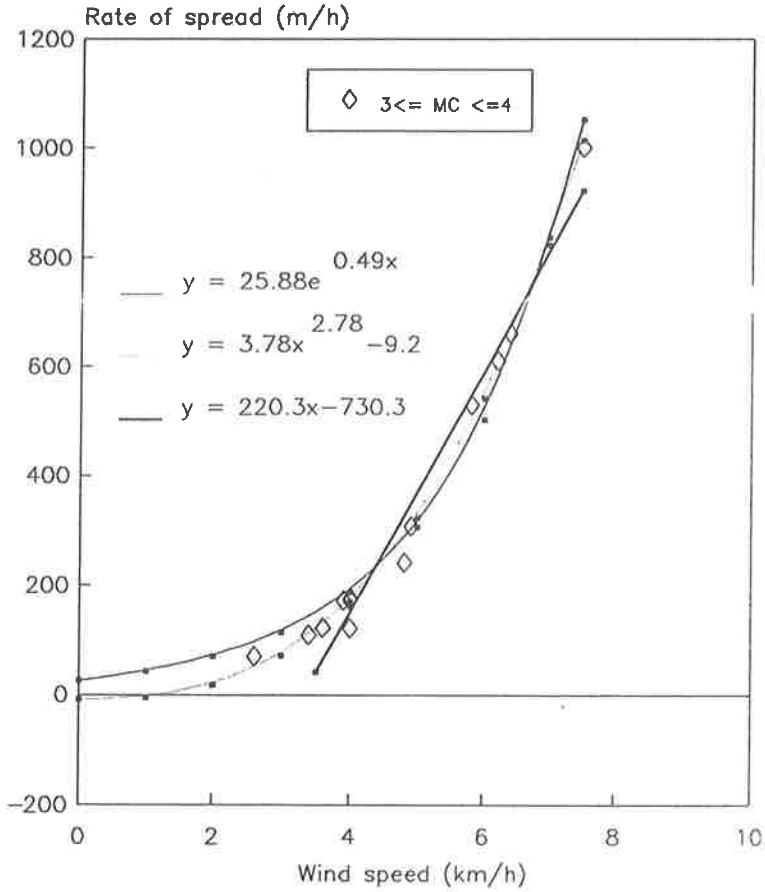
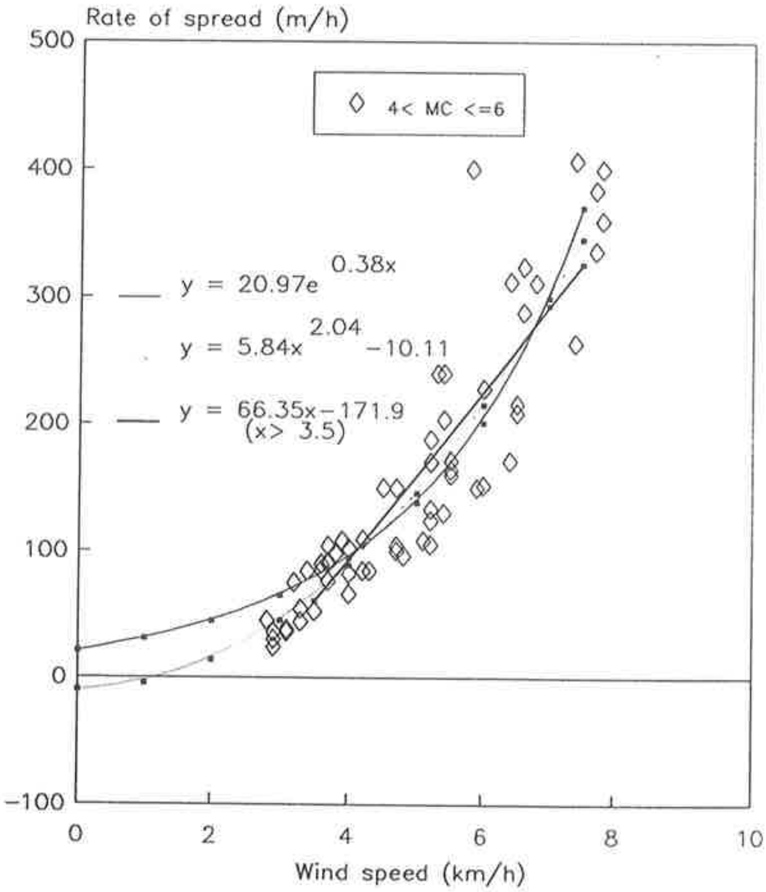
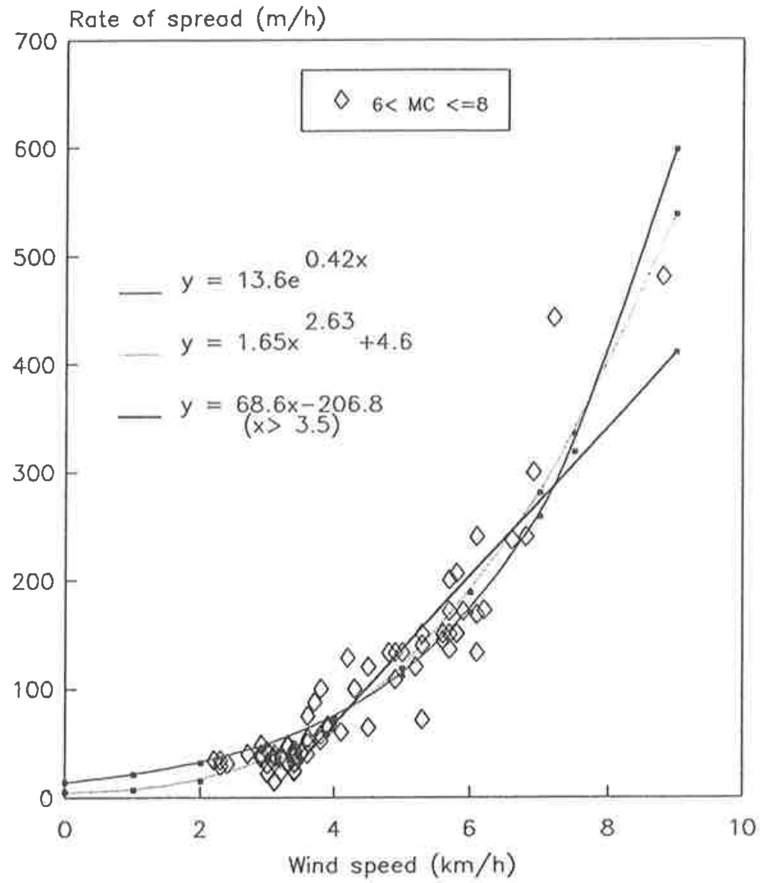


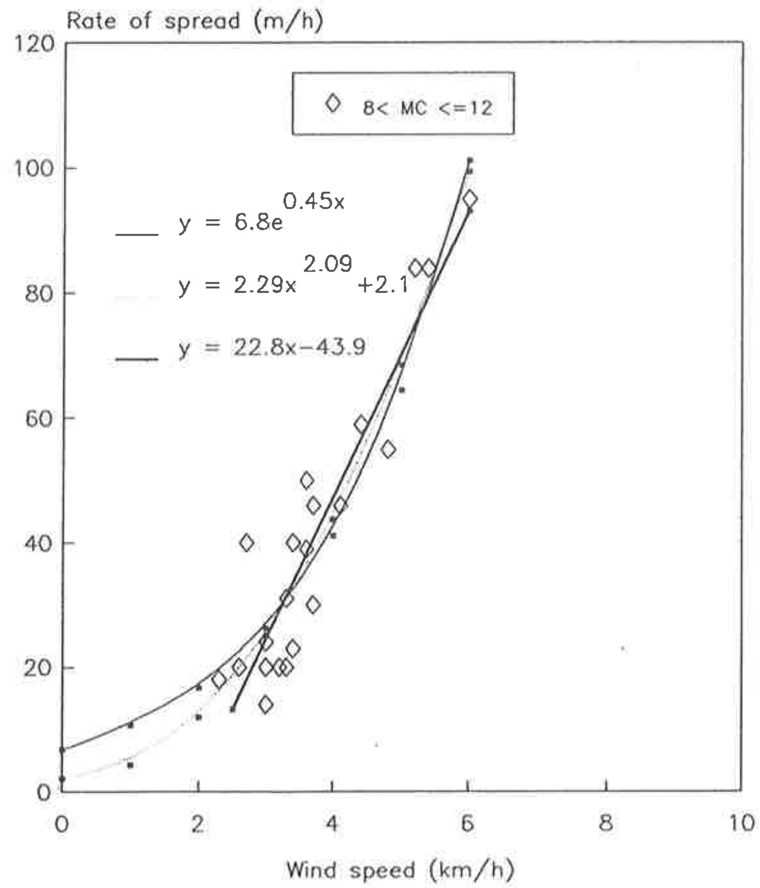
Figure 8-8: Headfire rate of spread with wind speed at 1.5 m in the forest, by fuel moisture (MC) classes. Candidate models are graphed. Regression statistics are contained in Table 8-4.







Rate of spread (m/h)
6< MC <=8
y = 13.6e^0.42x
y = 1.65x^2.63 +4.6
y = 68.6x-206.8 (x> 3.5)
Wind speed (km/h)
0
100
200
300
400
500
600
700
0
2
4
6
8
10



Rate of spread (m/h)
8< MC <=12
y = 6.8e^0.45x
y = 2.29x^2.09 +2.1
y = 22.8x-43.9
Wind speed (km/h)
0
20
40
60
80
100
120
0
2
4
6
8
10

McArthur (1961) and Underwood *et al.* (1985) summarised weather conditions and the behaviour of notable wildfires in jarrah forests and some of these data are contained in Table 8-5 below. The wind speed data were from 2-3 hourly observations made 25-30 km from the fires. It is not clear from McArthur's (1961b) tabulated summaries whether these observations are averages over the three hours or are spot readings made every three hours. The latter is most likely the case given the nature of the instruments used. The maximum wind speed recorded for each fire spread interval is presented in Table 8-5. Fuel moisture content was estimated from temperature and relative humidity data provided by McArthur (1961b) and Underwood *et al.* (1985) and using a relationship between fine fuel moisture content, temperature and relative humidity developed by Luke and McArthur (1978).

The observed wildfire data in Table 8-5 must be interpreted cautiously. Apart from doubts about the validity of using wind speed information from a distant station, these fires burnt in undulating terrain and often through different fuel types. In addition, headfire behaviour was probably influenced by intense downwind spotfire development commonly associated with jarrah forest fires under severe conditions. Despite these limitations, these data are a guide to the range of fire behaviour possible in south-west forests under severe fire weather conditions, which assists with appropriate model selection. In choosing between exponential and power equation forms, it was decided to risk slight under prediction at very low wind speeds by the power form than serious over prediction at high wind speeds by the exponential form (Table 8-5). It is also clear from Table 8-5 that while the power equation form fits the range of experimental data well, it over predicts rate of spread at very high wind speeds (not as seriously as the exponential). This suggests that the relationship between wind speed and rate of spread may be a sigmoidal one. Further research and carefully documented wildfire observations are needed to confirm the form of the relationship between wind speed and spread rate under extreme conditions.

The relationship between headfire rate of spread and surface fuel moisture content (SMC) was examined by stratifying the data according to wind speed classes (Figure 8-9) and fitting various models to the data. Of the candidate models shown in Table 8-6, the power form was the preferred model for the range of experimental data. Without the inclusion of a third parameter (constant) the power form presents a problem when SMC is 0%. In the field, SMCs less than 3% odw have never been recorded and it is highly unlikely that field SMC would ever reach 0% odw. At the other end of the moisture content range, the nonlinear relationships do not intercept the x-axis at moisture content of extinction, which for jarrah eucalypt litter bed is about 21% odw (Chapter 7).

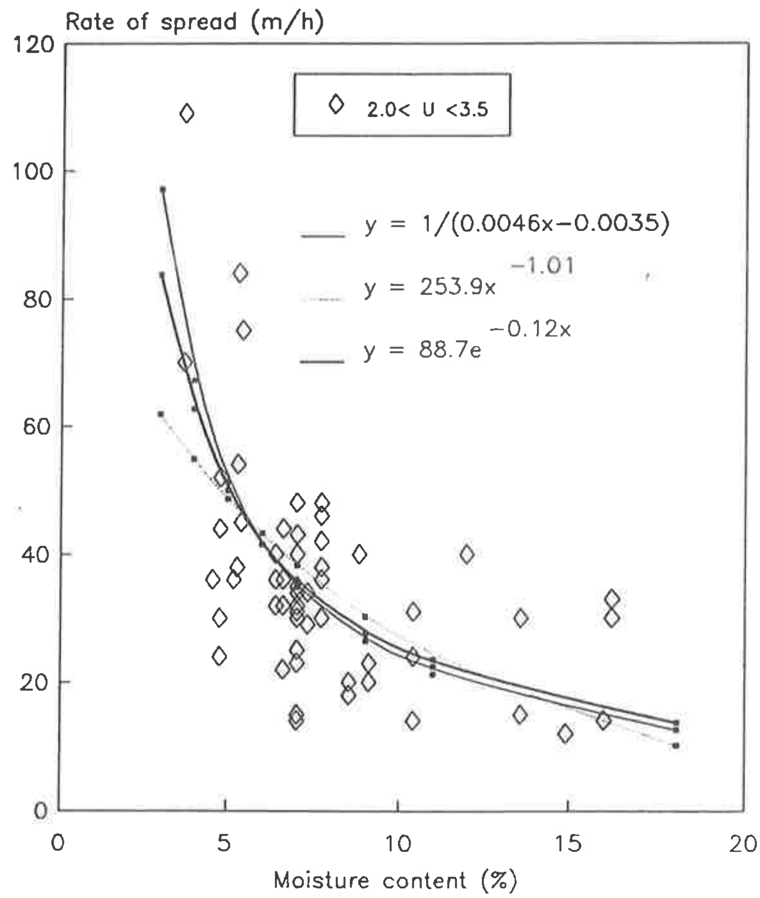
Table 8-5: Headfire rates of spread (ROS) and associated wind speeds observed during wildfires in various fuel types in the south-west of Western Australia are compared with rates of spread predicted by linear and non-linear models described in Table 8-3 for jarrah forest fuel and flat terrain. Surface fuel moisture content (SMC) was estimated using temperature and relative humidity (Luke and McArthur 1978). The tower wind speed-to-wind speed at 1.5 m in the forest (U) ratio is assumed to be 4:1 or 3:1 depending on forest type. The serious over-prediction by the exponential model at high winds and under-prediction by the linear one is clearly evident. (Source: McArthur 1961b and Underwood *et al.* 1985).

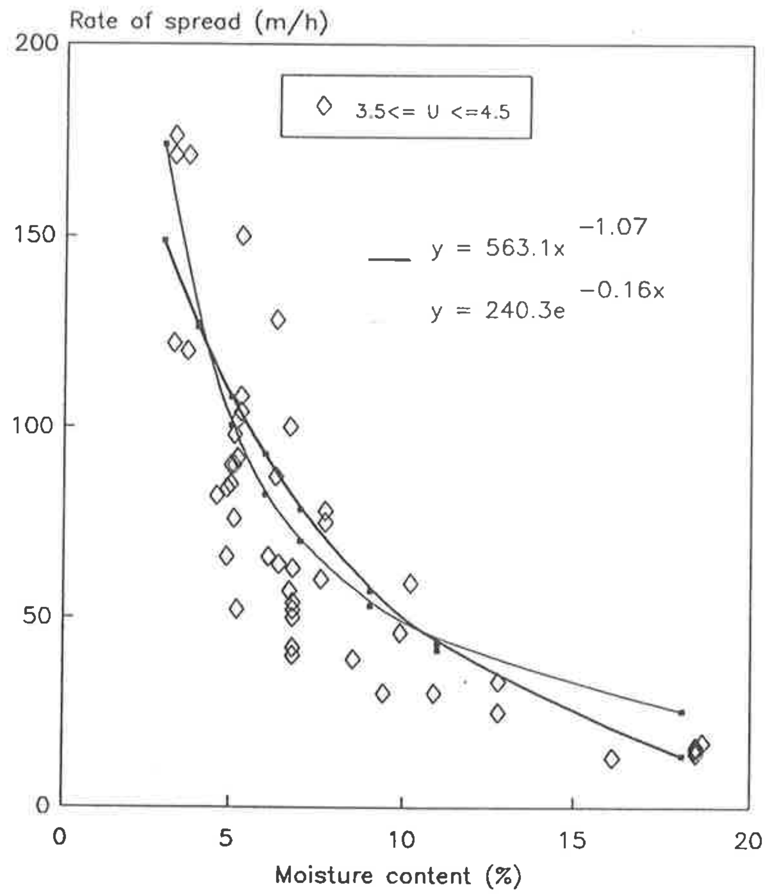
Fire	**Observed ROS ($m h^{-1}$)**	**U ($km h^{-1}$)**	**SMC (%)**	**Predicted ROS ($m h^{-1}$)**		
				Exponential	**Power**	**Linear**
McArthur (1961)						
Torrens	1,328	6.8	4	744	770	767
Marrinup	2,414	8.0	4	1,346	1,215	1,032
Duncans	1,609	8.0	4	1,346	1,215	1,032
Gidgegannup	2,343	8.8	4	1,999	1,587	1,208
Underwood *et al.* (1985)						
Rocky Gully	6,400	15.0	4	42,764	7,021	2,574
Lake Muir	1,000	6.6	4	674	735	723
Lake Muir	3,000	10.0	4	3617	2,268	1,473
Bruswick	8,000	20.0	4	50,558	15,644	3,676
Gervasse	10,000	25.0	4	5.97×10^6	29,082	4,777
Colonel's	400	6.2	4	553	603	635

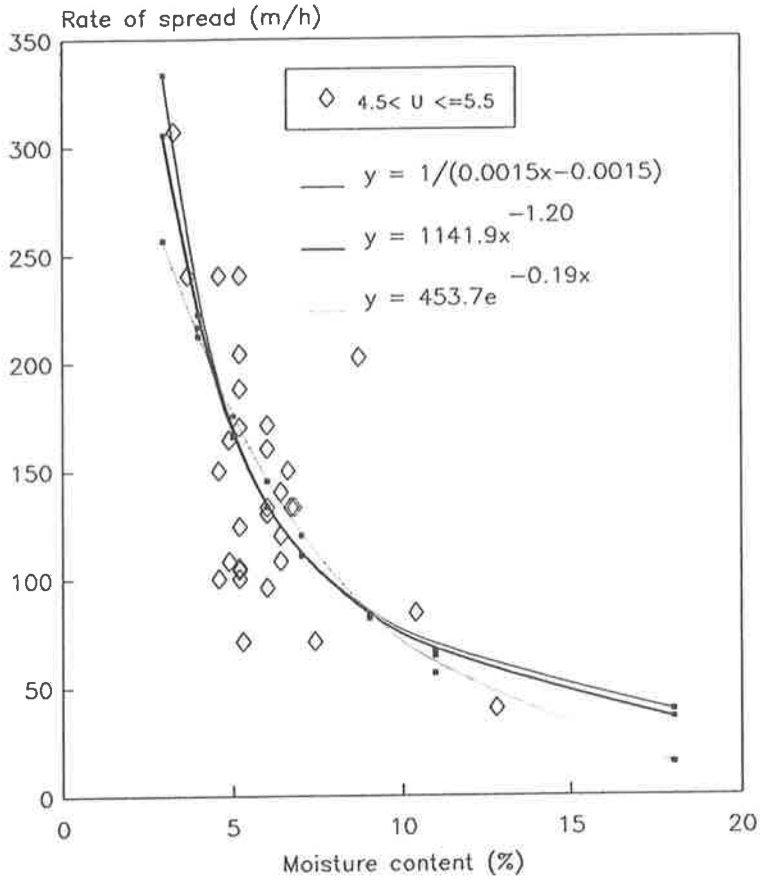
Table 8-5: Candidate models and associated statistics relating headfire rate of spread (r_F) and surface fuel moisture content (SMC) by wind speed classes (U). Equations graphed in Figure 8-9.

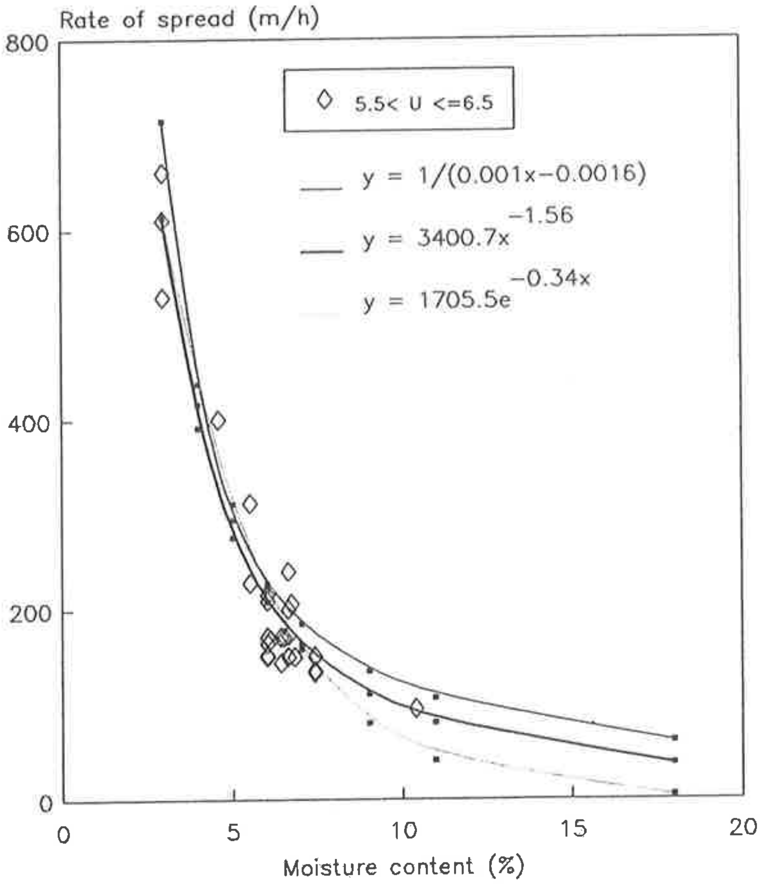
Equation r_F =	**S**	**s^2**	**Residuals Range**	**Residuals Mean**	**Precision**	**Bias**
		$2.0 <= U < 3.5$				
1/(0.0046SMC-0.0035)	0.41	158	-29.8-36.1	0.2	40.7	5.3
$253.9SMC^{-1.01}$	0.41	152	-28.0-41.6	0.0	38.1	2.7
$88.7e^{-0.12SMC}$	0.31	176				
		$3.5 <= U <= 4.5$				
1/(0.0022SMC-0.0035)	0.71	492	-35.9-56.8	0.0	29.2	-2.8
$563.1SMC^{-1.07}$	0.74	456	-36.8-55.4	0.6	28.5	-3.6
$240.3e^{-0.16SMC}$	0.72	481	-43.7-47.0	-2.4	27.2	1.2
		$4.5 < U <= 5.5$				
1/(0.0015SMC-0.0015)	0.62	1344	-85.1-81.2	-2.7	24.7	-1.2
$1141.9SMC^{-1.20}$	0.61	1369	-82.9-82.8	-0.9	25.0	0.2
$453.7e^{-0.19SMC}$	0.55	1560	-89.3-71.0	-6.3	28.8	0.9
		$5.5 < U <= 6.5$				
1/(0.001SMC-0.0016)	0.92	1840	-185.2-66.6	-34.0	49.8	-12.8
$3400.7SMC^{-1.56}$	0.92	1674	-83.7-85.4	-4.0	16.6	-2.2
$1705.5e^{-0.34SMC}$	0.92	1631	-86.0-59.1	-8.5	24.7	-0.8
		$U > 6.5$				
1/(0.00063SMC-0.00089)	0.80	6686	-101.6-214.8	-0.6	27.1	1.3
$5051.6SMC^{-1.49}$	0.79	7234	-104.4-223.9	-1.9	28.7	1.1
$2590.9e^{-0.33SMC}$	0.73	9195	-109.1-254.5	-3.9	35.1	2.1

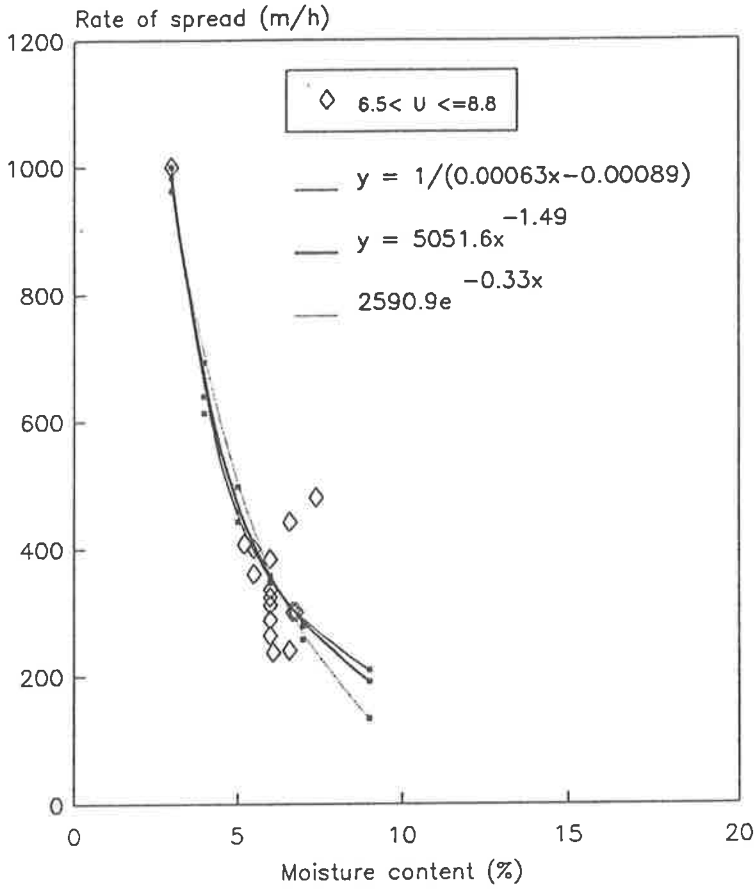
Figure 8–9: Headfire rate of spread with fuel moisture content by wind speed (U) classes. Candidate models are graphed. Regression statistics are contained in Table 8–6.






Rate of spread (m/h)
4.5< U <=5.5
y = 1/(0.0015x−0.0015)
y = 1141.9x^−1.20
y = 453.7e^−0.19x
Moisture content (%)


Rate of spread (m/h)
5.5< U <=6.5
y = 1/(0.001x−0.0016)
y = 3400.7x^−1.56
y = 1705.5e^−0.34x
Moisture content (%)



On the basis of the results presented in Tables 8-4 and 8-6, a headfire rate of spread prediction model incorporating a power function in wind speed and a power function in fuel moisture content was developed using a single nonlinear least squares fitting procedure (SAS Institute Inc. 1985). The final form of the model was:

$$r_F = 23.192(SMC)^{-1.495} * U^{2.674} + 11.60 \quad \textbf{(Equation 8-1)},$$

(4.036) (0.044) (0.095) (4.376) (parameter standard errors).

Data were transformed to linearize the relationship between rate of spread, wind speed and fuel moisture content. Natural log transformations on these variables resulted in the model;

$\ln(r_F) = 2.16(\ln U) - 1.05(\ln SMC) + 3.25 \quad R^2 = 0.85$,
where, r_F = headfire rate of spread ($m\ h^{-1}$), SMC = surface fuel moisture content (% odw), U = wind speed in the forest and 1.5 m above forest floor ($km\ h^{-1}$).

The analysis of variance and residual statistics for Equation 8-1 is contained in Table 8-7.

Table 8-7: Analysis of variance and residual statistics for regression Equation 8-1.

Source	DF	Sum of Squares	Mean Square
Regression	4	5861205.75	1465301.43
Residual	202	201653.92	849.04
U/C Total	206	6032712.99	
C Total	205	3335664.25	

Residuals

Range	Mean	Bias	Precision
92.1-159.6	0.097	0.50	29.48

Residuals (observed rate of spread minus that predicted using Equation 8-1) are graphed in Figure 8-10. Residuals were checked for normality by examining their frequency distribution (Figure 8-11), the Shapiro-Wilk (W) statistic (SAS Institute Inc. 1985), skewness and kurtosis (0.946, 0.910 and 5.516 respectively). These statistics support the null hypothesis that the residuals are normally distributed and variance is homogeneous.

Figure 8-10: Residuals (observed rate of spread - predicted rate of spread) graphed with predicted rate of spread.

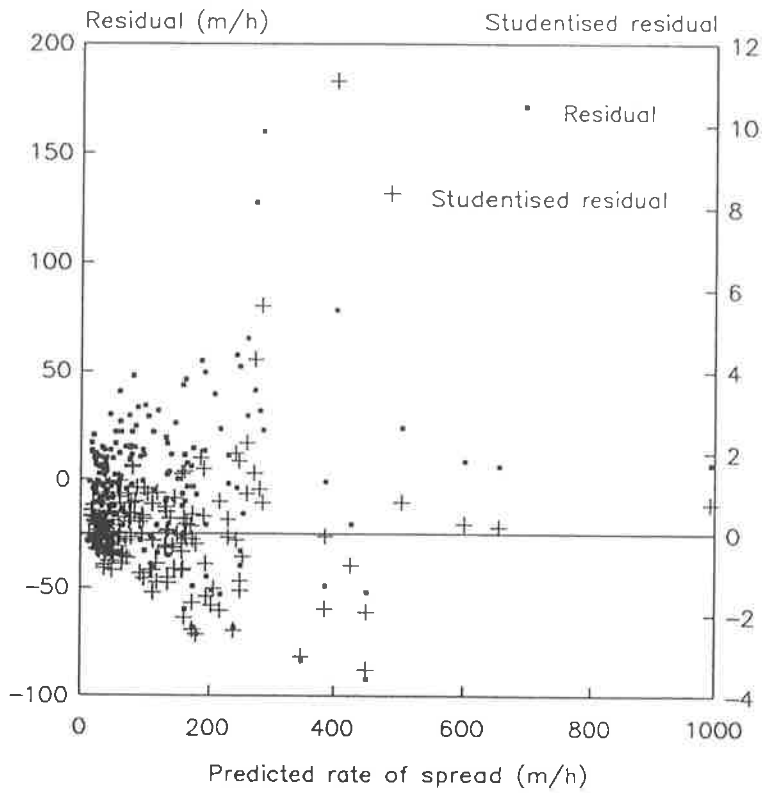


Figure 8-11: Frequency histogram of residuals (observed rate of spread - predicted rate of spread).

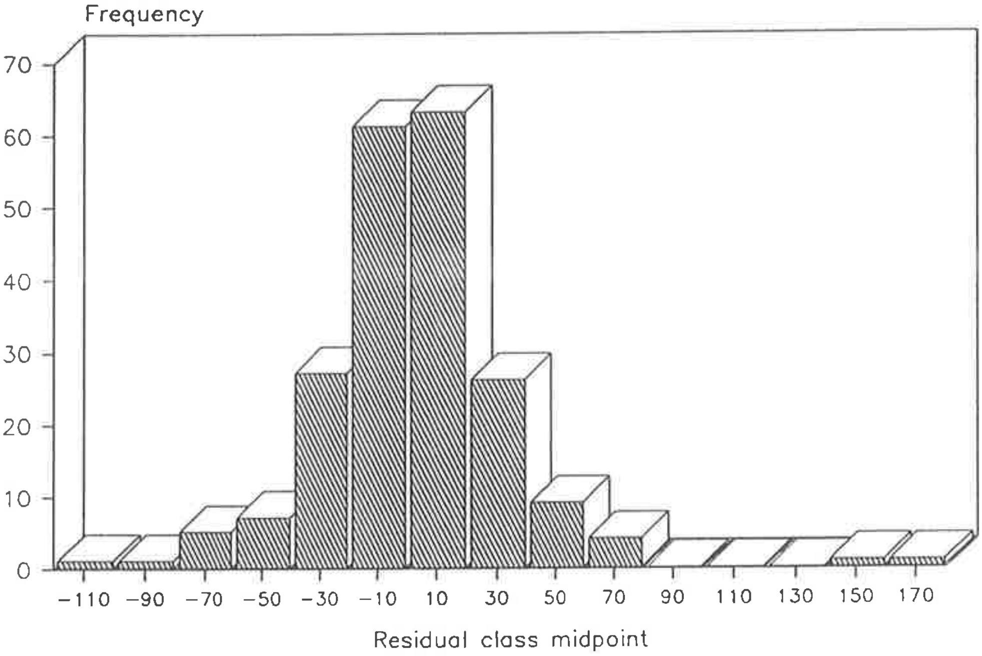
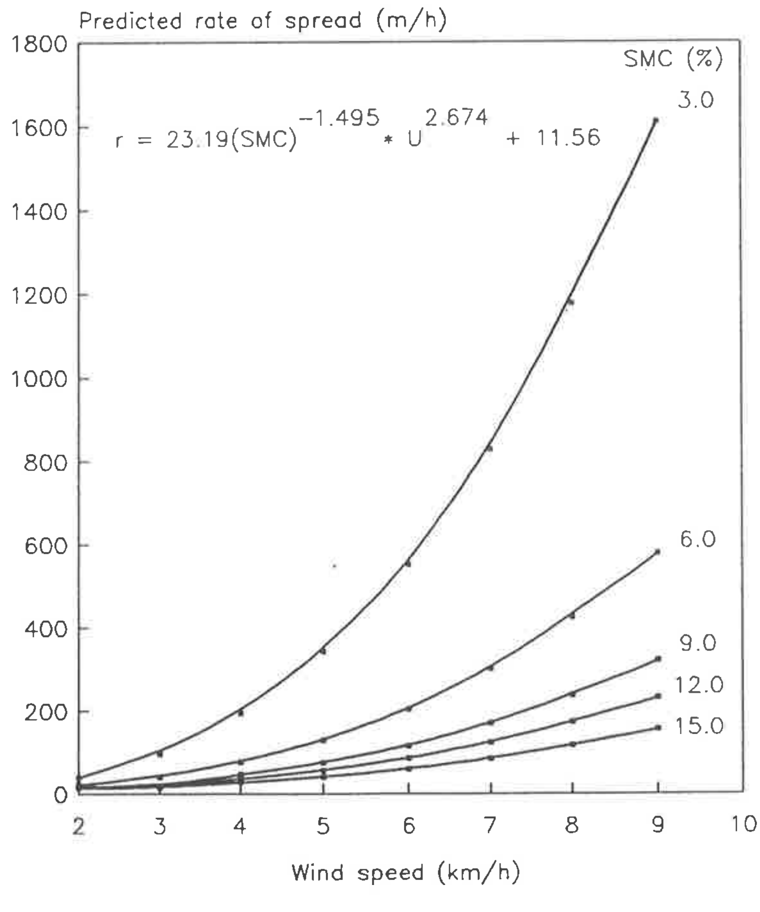


Figure 8-12: Rate of spread prediction model for jarrah forest fuel. r = headfire rate of spread, SMC = surface fuel moisture content and U = wind speed at 1.5 m in forest.



Residual outliers coincide with fire spread intervals where wind gusts were observed at the fire face but not recorded by the anemometers and vice versa. Rate of spread predicted using Equation 8-1 is graphed for 5 surface fuel moisture contents in Figure 8-12.

Headfire rate of spread was poorly correlated with fuel quantity for the laboratory experiments described in Chapter 7. The relationship was equally poor (Table 8-2) for field data where the average rate of spread over selected time intervals (intermediate rates of spread) within each plot was regressed with mean fuel quantity burnt over the same interval (see Methods section 8.2.3). Headfire rate of spread is graphed with fuel quantity by wind speed classes in Figure 8-13 with no relationship between the two variables. The relationship was further examined using whole plot data where the mean plot rate of spread and the mean plot fuel quantity were analysed on the assumption that estimates of mean fuel quantity over the entire plot (see Methods section 7.2.2) may better reflect fuel involved in headfire spread. However, this procedure also failed to show any significant relationship between headfire rate of spread and fuel quantity (Pearson correlation coefficient = -0.165). Mean plot headfire rate of spread is graphed with mean plot fuel quantity in Figure 8-14. Eliminating variation in rate of spread due to wind speed and moisture content using Equation 8-1 also failed to show any significant relationship between rate of spread and fuel quantity.

The lack of a relationship between headfire rate of spread and litter fuel quantity reported in this study contrasts with widely held beliefs within the Australian fire community and with commonly used Australian forest fire behaviour guides (McArthur 1962, Peet 1965 and Sneeuwjagt and Peet 1979) which assume that spread rate is directly related to fuel quantity. Cheney *et al.* (1989) and Gould (1991) found that the rate of spread in grassland fuels was not related to fuel quantity but was related to fuel height. Cheney (1990b) also noted in a discussion paper that statistical support for the notion that rate of spread and fuel quantity are directly related was "difficult to find".

McArthur and Luke (1963) and McArthur (1967a) reported a positive linear correlation between rate of spread and available fuel quantity for jarrah forest fires; doubling fuel quantity caused a doubling of rate of spread (Figure 8-15). McArthur's (1961b and 1967a) relationship was derived by comparing the rates of spread of wildfires in different fuel ages (and quantities) and by monitoring the development of experimental fires lit simultaneously in forest and woodlands of different fuel age (and different fuel quantity). Data from nine experimental fires lit in jarrah forests were extracted from Leaflet 107 (McArthur 1967a) and a linear regression model fitted to these data (Figure 8-15). These fires were set in very light fuels and, based on the low rates of spread, burnt under mild weather conditions. The data show a strong linear relationship between rate of spread and fuel quantity which contrasts with the findings of this study.

Figure 8–13: Mean headfire rate of spread with mean fuel quantity by wind speed classes. Multiple observations from each plot.

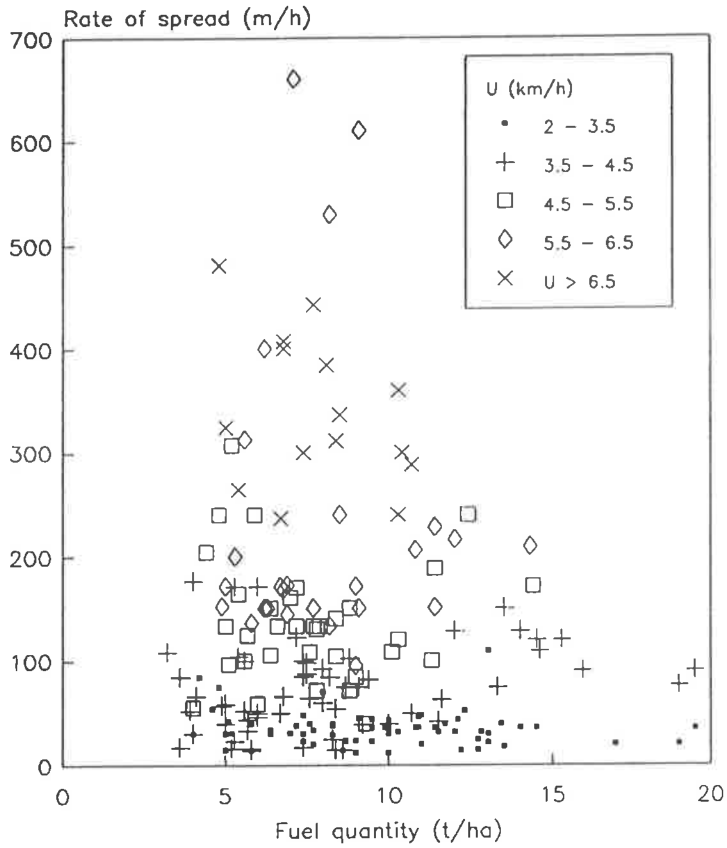
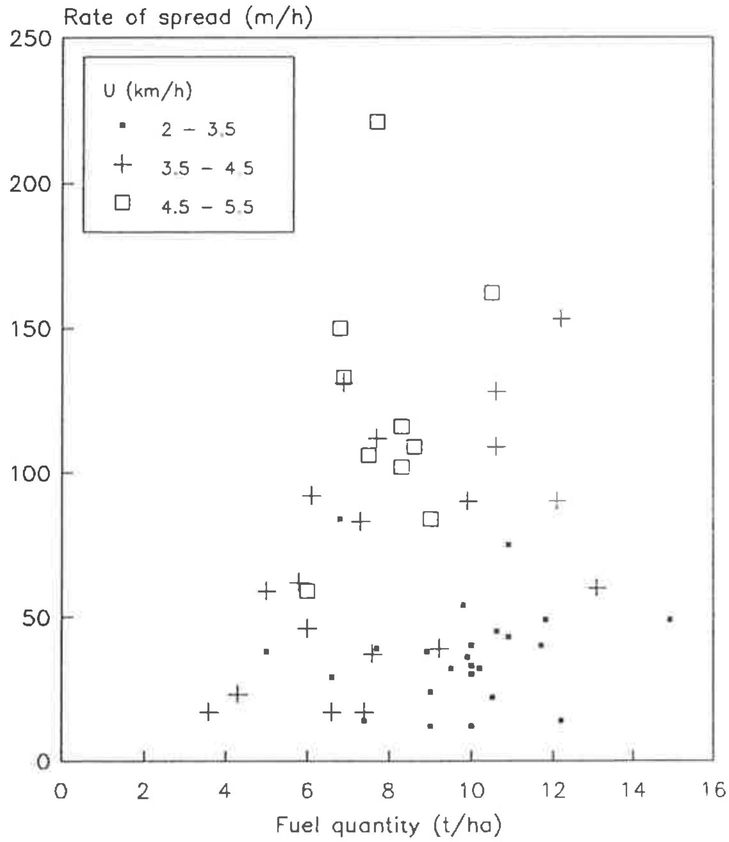


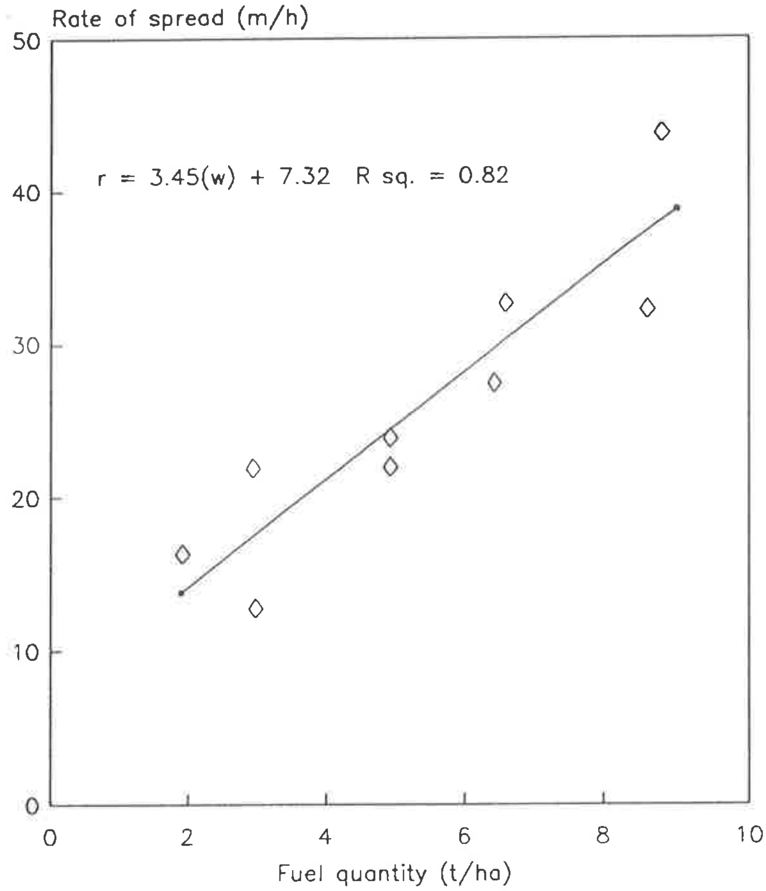
Figure 8–14: Mean headfire rate of spread with mean litter fuel quantity by wind speed (U) classes. Single observation per plot.



There are three possible explanations for the contrast in findings. The first possibility is that rate of spread is in fact affected by fuel quantity but the experimental procedures adopted here failed to demonstrate this. Secondly, it is possible that in McArthur's experiments, fire behaviour was responding to fuel structural differences associated with the various ages and not to fuel quantity *per se*. This could not be examined by this study because of the narrow range of fuel ages. Data presented in Chapter 5 above show that after the first 4 years following fire, the structure of litter bed does not vary significantly but the fraction of fine round wood increases with time. Fine round wood is the most flammable component of the litter bed (Chapter 6). The structure of the understorey vegetation changes with time after fire and for up to 20 years (Chapter 5). Temporal changes in the composition of the litter bed and in the structure of the understorey are likely to affect fuel flammability. Another explanation is that the jarrah fires studied by McArthur were not wind driven, but were largely convection dominated fires (i.e. flames virtually erect). The fires were lit from a point source and were monitored for some 20-30 minutes. The very low rates of spread of these fires (Figure 8-15) suggests that they burnt under very light winds, probably below the threshold for wind driven headfire development (no meteorological data are presented). If this was the case, then these fires were probably behaving similarly to backfires and sub-threshold wind speed (<3.5 km h^{-1}) fires reported in Chapter 7. Unlike wind driven fires, the rates of spread of low wind fires and backfires were found to be dependent on fuel quantity in much the same way as reported by McArthur (see Chapter 7). McArthur (1967a) does not provide sufficient detail about fuel structure and weather conditions to allow a thorough interpretation of his findings with regard to the effect of fuel quantity on rate of spread.

Peet (1972) reported a poor relationship between fuel quantity and rate of spread for small, low intensity jarrah litter fires both in the field and during "tray" experiments. However, he felt that this was due to poor fuel sampling techniques in the field, so opted to use the linear relationship developed by Fons (1946) and McArthur (1962) when developing the first version of Forest Fire Danger Rating guides for Western Australia (Peet 1965).This relationship was carried through to updated guides.The 1979 edition of FFBT incorporates a fuel quantity correction factor for predicting rate of spread such that at low moisture contents (3-9%), doubling fuel quantity results in a two-fold increase in predicted rate of spread (Sneeuwjagt and Peet 1979). This is similar to the relationship developed in the laboratory studies reported above (Chapter 7) for zero wind fires and backfires. It is possible that the original relationship between rate of spread and fuel quantity (Fons 1946) was developed under zero or sub-threshold wind conditions, where radiation is the primary spread mechanism, and was assumed to hold for wind driven fires, where forced convection (flame contact) is probably the primary spread mechanism.

Figure 8-15: Linear regression fitted to McArthur's (1967) rate of spread and fuel quantity data derived from small experimental fires in jarrah forest.



Nelson and Adkins (1987) have proposed that the horizontal displacement of flame at the fuel surface, by a convection mechanism related to wind speed, is the key to fire spread. Results reported here support this theory. The quantity of fuel undergoing combustion in the flaming zone, *ceteris paribus*, is a function of horizontal flame depth and the rate of vertical depth of burn into the fuel profile (Byram 1959). As discussed in Chapter 7, this may not be a function of fuel quantity *per se* but of fuel particle size and arrangement, packing ratio and fuel bed bulk density, as recognised by models developed by Rothermel (1972) using artificial fuel beds. Jarrah litter fuel has a high bulk density and a high packing ratio, and individual particles have a low surface area-to-volume ratio (Chapter 5) compared with grassland and heathland fuels (e.g. Rothermel 1972 and Catchpole 1985). The mean packing ratio for jarrah litter fuel is about 0.079, based on the linear depth - weight relationship presented in Chapter 5. Blake and Johnson (1973) found that the packing ratio of the litter in a eucalypt forest in New South Wales varied considerably, but was mostly greater than 0.07. Eucalypt litter fuel beds are very compacted compared with some other litter bed fuel types. For example, Brown (1970) determined a packing ratio of 0.03 for ponderosa pine forest needle litter. The optimum packing ratio for eucalypt litter fuel particles, using Rothermel's (1972) equation, is about 0.006, so jarrah forest litter is far from an optimum fuel according to this definition. Significant increases in rate of spread with increasing fuel quantity are only likely in fuel beds at or near optimum packing ratio (Rothermel 1972, Chandler *et al.* 1983). For poorly aerated, compacted fuel beds, the rate of flame spread across the surface of the fuel bed, where aeration is best, will be considerably greater than the rate of combustion vertically through the fuel bed. Therefore, most of the heat energy for flame propagation will be provided by the combustion of surface particles in the forward portion of the flaming zone, with the combustion of particles deeper in the fuel bed occurring progressively further behind the leading edge, and so contributing little or nothing to flame propagation. If bulk density and packing ratio are constantly high with increasing fuel quantity (as is more or less the case with jarrah litter fuels), then changes in fuel quantity are unlikely to significantly affect rate of spread. Observed higher spread rates in old and heavy eucalypt fuels (not including fire perimeter extension by spotting or crown fire development) is probably in response to changes in fuel composition and structure. This is likely to be particularly important in forests with a dense understorey. The effect of temporal changes in eucalypt forest fuel structure on fuel flammability requires further investigation.

8.3.2 Rate of spread predicted using the Forest Fire Behaviour Tables

Headfire rate of spread observed during these experiments is graphed with headfire rate of spread predicted using the Forest Fire Behaviour Tables for Western Australia (FFBT) (Sneeuwjagt and Peet 1979) in Figure 8-16. Predictions were made using actual weather and fuel moisture content data rather than forecast data. A wind speed ratio of 1:1 (i.e. wind speed measured in the forest at 1.5 m) was used and normal procedures for correcting for fuel quantity were followed.

The FFBT 1979 edition under estimates the rate of spread of fires spreading faster than about 50-60 m h^{-1} by a factor of about 1.6 on average (Figure 8-16) and over estimates the rate of spread of slower fires burning under light winds. The correlation coefficient (R^2) for the regression graphed in Figure 8-16 is 0.59, indicating a poor linear relationship between predicted and observed rates of spread. The FFBT over estimated the influence of low fuel moisture content on spread rate at very low wind speeds (< 3.5 km h^{-1}). For example, at a wind speed of 2 km h^{-1} (1:1 wind speed ratio) and a moisture content of 3%, the FFBT predicts a spread rate of 148 m h^{-1} in standard jarrah fuel, compared with a prediction of 40 m h^{-1} using Equation 8-1.

The jarrah FDI (Sneeuwjagt and Peet 1979) is defined as the maximum rate of spread predicted from wind speed and surface fuel moisture content under standard conditions, i.e. on level terrain and in jarrah litter fuels of 7.6-8.5 t ha^{-1}. For other than standard conditions, slope and fuel quantity correction factors are applied to the FDI for predicting rate of spread (Sneeuwjagt and Peet 1979). The FDI, or the predicted rate of spread under standard conditions, is graphed with observed rate of spread in Figure 8-17. Although the predictions are lower than observations, the correlation coefficient is significantly better ($R^2 = 0.78$) than that for predictions which have been corrected for fuel quantity ($R^2 = 0.59$, Figure 8-17).

While about 20% of the variation between FFBT predictions and observed rates of spread can be explained by the FFBT assumption that there is a strong relationship between rate of spread and fuel quantity, this does not account for under prediction at higher wind speeds. The magnitude of under prediction cannot be totally explained by the fact that Peet's (1972) wind speed measurements were made at four feet (1.4 m) compared with 1.5 m during this study. The most likely explanation is that Peet's experimental fires were mostly small, slow spreading and lit from a point source under generally mild conditions (see Chapter 4). It is possible that the fires were accelerating and had not reached their potential rate of spread in the small plots. Prediction models developed from these data have resulted in serious under-estimation of rate of spread on extrapolation.

8.3.3 Rate of spread predicted using the McArthur Forest Fire Danger Meter

Headfire rate of spread predicted using McArthur's Forest Fire Danger Meter (FFDM) equations developed by Noble *et al.* (1980) are graphed with observed rate of spread in Figure 8-18 and McArthur's Forest Fire Danger Index (Mark 5) is graphed with observed rate of spread in Figure 8-19. The relationship between predicted (FFDM) and observed rate of spread is very poor ($R^2 = 0.26$) with the FFDM over predicting during conditions of low fuel moisture, low wind speeds and high fuel quantities, and seriously under predicting (by a factor of up to 3) during conditions of high wind speeds and low fuel quantities. A better relationship was obtained between McArthur's Forest Fire Danger Index and observed rate of spread (Figure 8-19).

8.3.4 Rate of spread predicted using the Rothermel Model

Observed rates of spread are plotted with predictions made using Rothermel's (1972) model in Figure 8-20. Jarrah fuel parameter values used in the Rothermel model (e.g. packing ratio, surface area-to-volume ratio) are described in Chapter 5 and are summarised in Appendix 3. Weather and fuel moisture content inputs were measured in the field, with wind speed measured at 1.5 m and not at mid-flame height, as required by the Rothermel model. Equations used to calculate the Rothermel predictions in metric units are contained in Appendix 3.

Figure 8-16: Rate of spread predicted using the FFBT (1979 edition) with observed rate of spread.

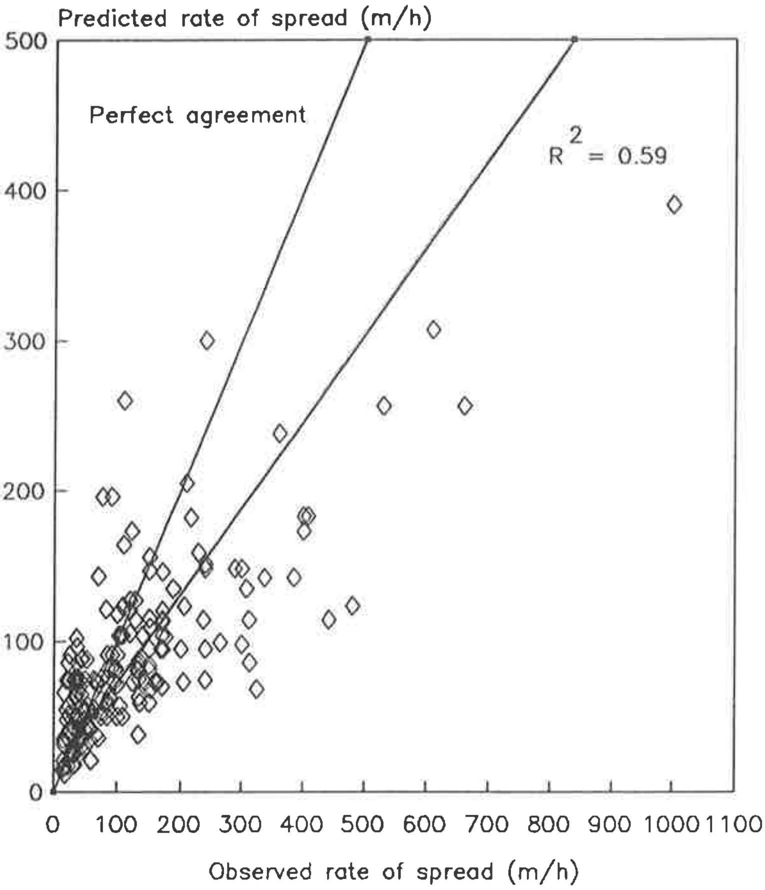


Figure 8-17: Jarrah Fire Danger Index (FDI) (Sneeuwjagt and Peet 1979) with observed rate of spread. The FDI is equal to the expected rate of spread in standard fuels, no slope.

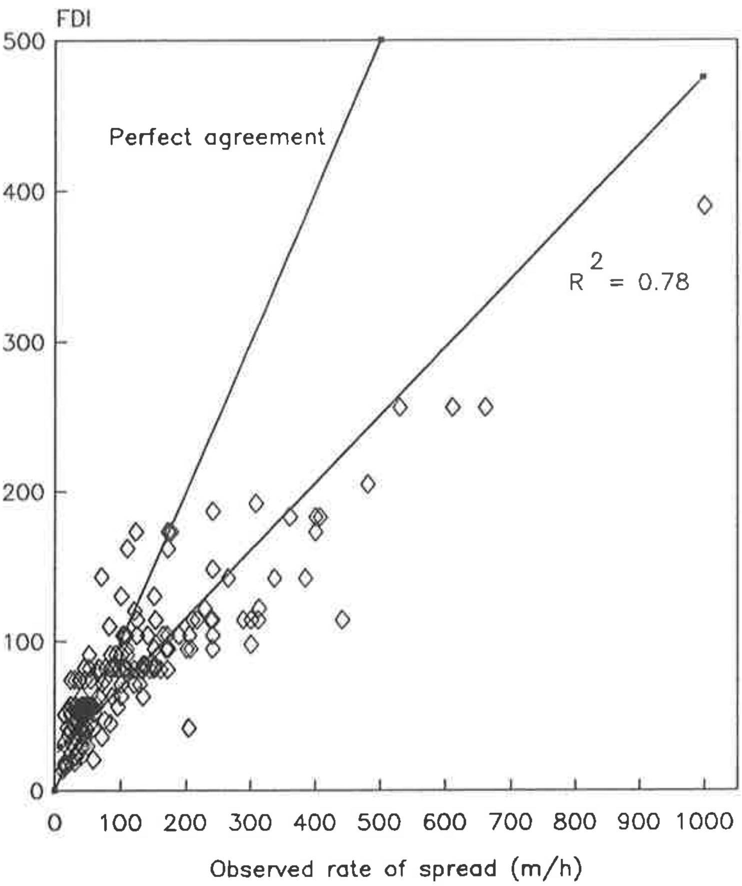


Figure 8–18: Rate of spread predicted using the McArthur Forest Fire Danger Meter with observed rate of spread.

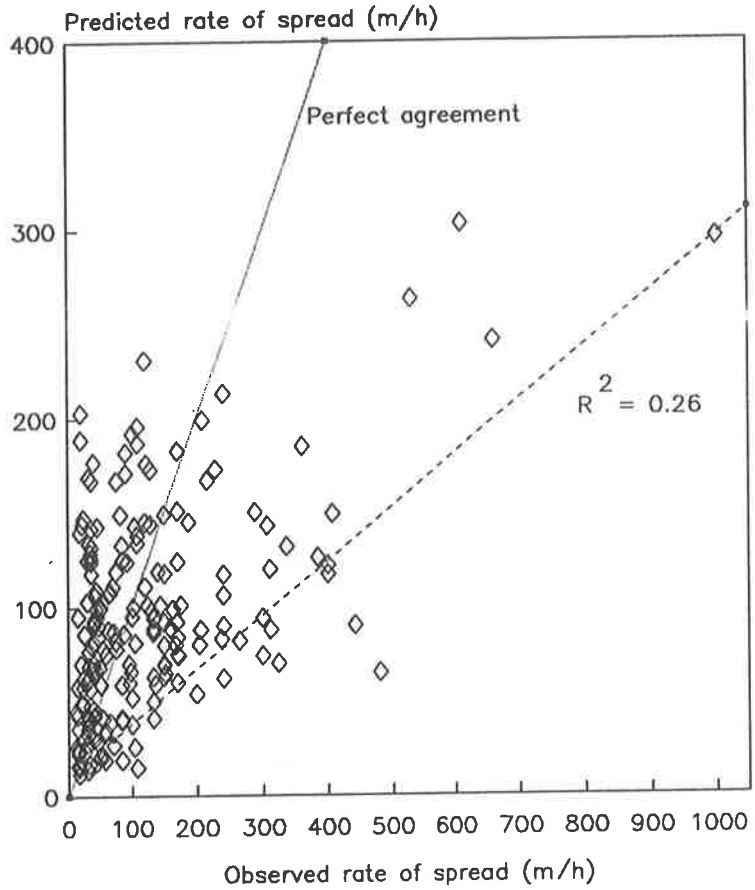


Figure 8–19: McArthur's Forest Fire Danger Index with observed rate of spread.

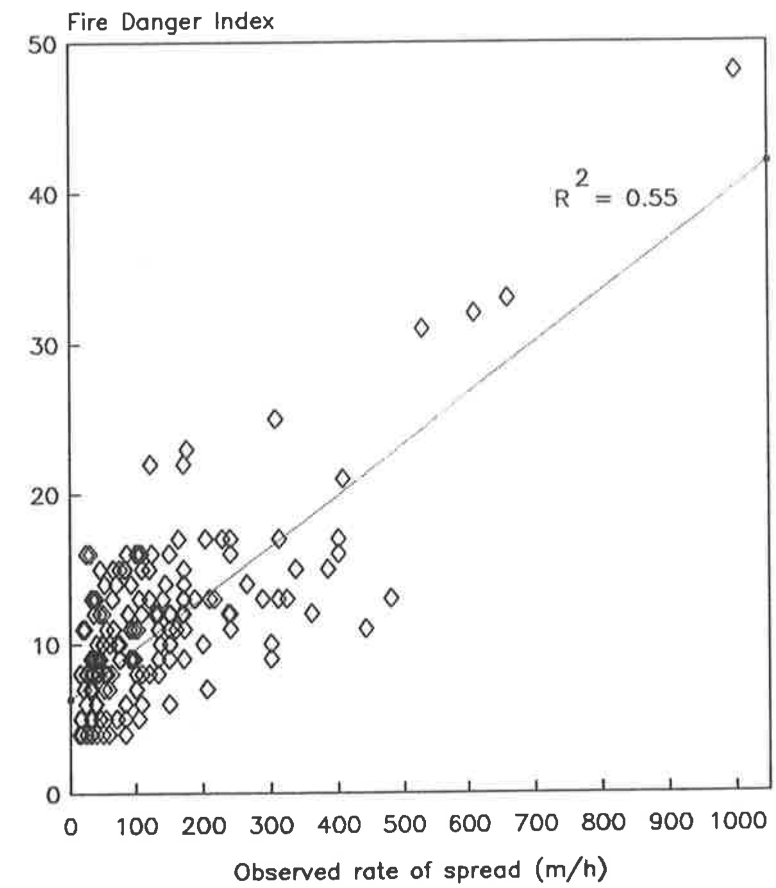
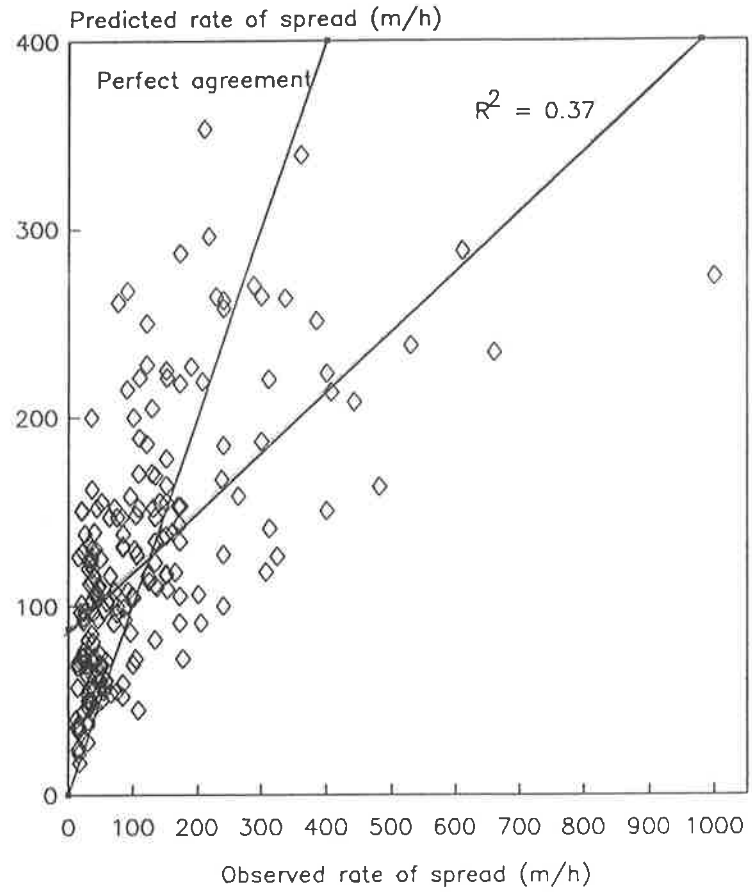


Figure 8–20: Rate of spread predicted using Rothermel's (1972) model with observed rate of spread.



As with the McArthur model, the Rothermel model over predicts rate of spread when wind speeds are low (<3.5 km h^{-1}) and when fuel quantities are high. Both models assume a direct relationship between fuel quantity and rate of spread. The model seriously under predicts the spread rate of fires burning under high wind speeds and low fuel moisture contents although the Rothermel model makes marginally better predictions than the McArthur model (R^2 = 0.37).

The Rothermel model has been tested for a number of fuel types including slash fuels (Brown 1971), grassland (Sneeuwjagt and Frandsen 1977, Van Wilgen and Wills 1988, Everson *et al.* 1988 and Gould 1991), palmetto-gallberry (Hough and Albini 1978), fynbos (Van Wilgen 1984) and heathland (Catchpole 1985) and was found to perform reasonably well in most cases, with R^2 values (actual vs predicted rate of spread) of 0.89-0.92. However the model performed poorly during grassland experiments conducted in the Northern Territory (Gould 1991) with an R^2 (actual vs predicted rate of spread) of 0.55. In all cases, fuels were considerably deeper and more aerated than the jarrah litter fuel bed described here. Andrews (1980) summarized the results of most of these validation studies and also compared Rothermel predictions with spread rates observed during several wildfires. No fuel, weather or topographical details are provided for the wildfire conditions, but in all cases, the Rothermel model performed considerably better than reported here.

8.3.5 Flame Dimensions and fire intensity

Flame height and length are important measures of the heat energy output of a fire, hence its severity both in terms of control difficulty and impact on the biota (Byram 1959 and Luke and McArthur 1978). Accurate measurements of flame dimensions are difficult to obtain in the field, especially for moderate to high intensity fires. The ocular method used during this study may not have been accurate, but it was reasonably precise, with the observers showing an acceptable level of consistency with estimations. Headfire flame height (h_F) increased with headfire rate of spread (r_F) according to Equation 8-2. Predictability of flame height was improved by incorporating fuel quantity (w_C) as shown in Equation 8-3. Flame size was a consequence of factors affecting rate of spread (wind speed and fuel moisture content) and fuel quantity; large flames did not cause fires to spread faster, but were a consequence of these factors. Flame height is graphed with rate of spread by fuel quantity classes in Figure 8-21. Flame length (L) was strongly related to flame height by Equation 8-4.

$h_F = 0.062(w_C)^{0.687}$ (Equation 8-2),
$h_F = 0.00335(W_H) * w_C$ (Equation 8-3),
$L = 1.33h_F$ (Equation 8-4),

where h_F = flame height (m), L = flame length (m), r_F = rate of spread (m h^{-1}), and w_C = fuel quantity (t ha^{-1}). Analysis of variance for the above equations are contained in Appendix 2.

The general form of flame height and length relationships presented above are similar to those reported for other fuels (e.g., Byram 1959, McArthur and Cheney 1966 and Luke and McArthur 1978).

Byram (1959) derived an equation approximating the relationship between flame length and fire intensity (Figure 8-22). Other fire researchers have rearranged this equation to determine fire intensity from direct observation of flame length (see Alexander 1982). The relationship between flame length and fire intensity for standard jarrah fuel was;

$L = 0.0147(I)^{0.767}$ (Equation 8-5),

where L = flame length (m) and I = Byram's intensity (kW m^{-1}).

Equation 8-5 is graphed in Figure 8-22 with Byram's (1959) relationship. The coefficients in the equations shown in Figure 8-22 are significantly different, resulting in considerable divergence of predictions of intensity with increasing flame length beyond a flame length of about 1.5-2.0 m. Byram's (1959) equation predicts significantly higher intensities for a given flame length than Equation 8-5. Although Byram (1959) warned that his relationship would give better approximations for low than for high intensity fires, it is possible that equation coefficients may vary with fuel type, reflecting different flame characteristics. For example, Cheney (1981) estimates that a moderate intensity (501-3,000 kW m^{-1}) fire in open *Eucalyptus* forest will have a maximum flame height of 6.0 m (therefore a flame length greater than 6 m, probably near 8 m). Using data from Luke and McArthur (1978) (Figure 6.15, page 93), a fire in dry sclerophyll (open *Eucalyptus*) forest with an intensity of about 2,500 kW m^{-1} will have an estimated flame height of 5-7 m (length about 6.6-9.3 m) depending on wind speed. These values are similar to those presented in Figure 8-22 for jarrah forest. However, Byram's (1959) equation, presumably developed from observations of North American conifer forests, predicts that a fire with an intensity of 3,000 kW m^{-1} will have a flame length of about 3.1 m. Clarke (1983), working in grassland fuels, reported a fire intensity-flame length relationship which differed to that presented by Byram (1959) and concluded that flame length was neither a good nor consistent estimator of fire intensity.

Figure 8–21: Headfire flame height (h) with rate of spread (r) by fuel quantity (w) classes.

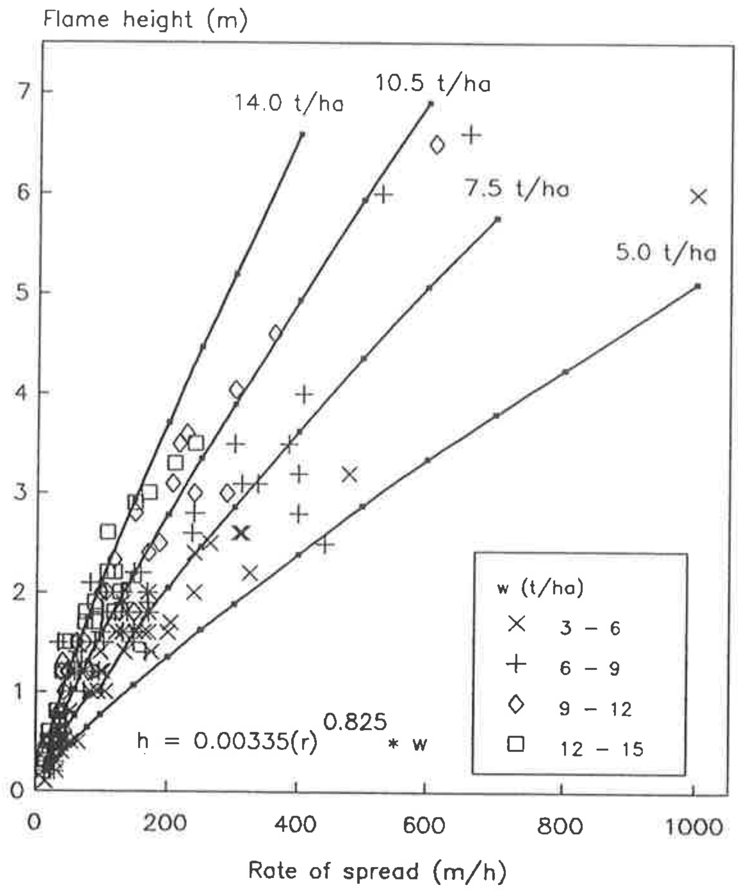
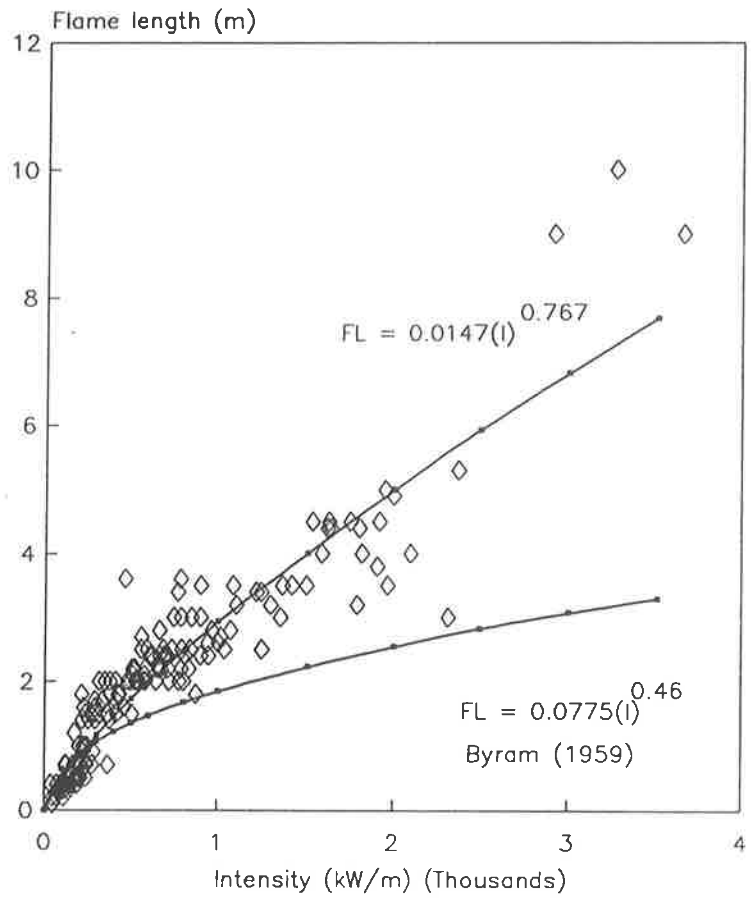


Figure 8–22: Flame length with fire intensity. Byram's (1959) relationship is graphed for comparison.



Fire intensity can be predicted from observed flame length by rearranging Equation 8-5 as follows;

$I = 293.871(L)^{1.118}$ (Equation 8-6).

Byram's (1959) equivalent equation is (after Alexander 1982);
$I = 259.833(L)^{2.174}$

Clearly, the equations will predict significantly different intensities for a given flame length confirming recommendations by Alexander (1982) and Cheney (1990a) that fire intensity should not be used to make comparisons between fires in different fuel types.

8.3.6 Flame residence time

Flame residence time (t_R - seconds), as defined by Fons *et al.* (1962), was calculated from flame depth and headfire rate of spread (Cheney 1981) and is graphed in Figure 8-23 with fuel quantity, the only variable to show a reasonable correlation with residence time (Pearson correlation coefficient = 0.55). As indicated by the plotted data and by the low R^2 value for the no intercepts model, the relationship is a poor one reflecting unmeasured variation in fuels, the difficulty of accurately measuring flame depth and natural, unexplained variation. McArthur (1967a) reported a decrease in residence time with increasing wind speed and decreasing fuel moisture content for eucalypt litter fuel beds in the field, but laboratory studies reported in Chapter 7 above and studies by Byram *et al.* (1966) and Rothermel and Anderson (1966) found residence time to be unaffected by these variables.

Flame residence times observed during the field fires were considerably longer than the times reported for the laboratory studies in Chapter 7 for similar fuel quantities. The difference may be attributable to the different composition of the fuel beds; only fresh (L horizon) leaf and twig material were used in the laboratory whereas field fuels consist of L and H layers and a component of larger woody material.

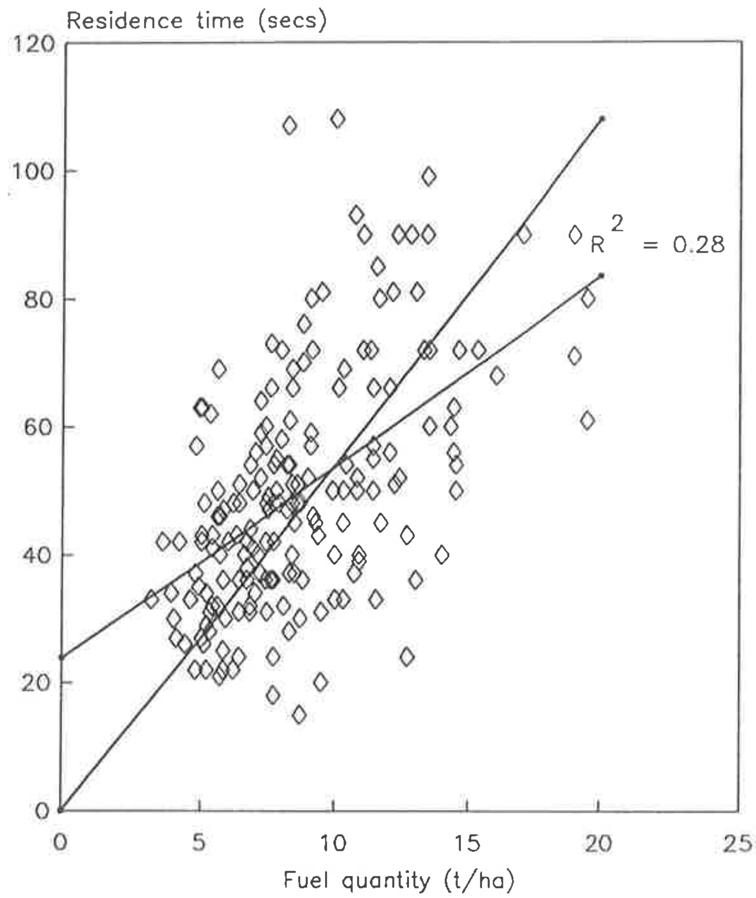
8.4 Concluding discussion

Headfire rates of spread up to 660 m h^{-1} were recorded during fire experiments described in this study which is significantly higher than previously reported by other eucalypt forest fire behaviour experiments. Observed rates of spread were up to three times faster than predicted using existing eucalypt forest fire behaviour guides.

Most variation in rate of spread could be explained by wind speed and fuel moisture content. Headfire rate of spread was found to be independent of litter fuel quantity providing there was sufficient fuel to sustain a running fire (more than about 4.0 t ha^{-1}). A new jarrah forest fire danger rating and fire behaviour prediction model incorporating a power function in wind and a power function in fuel moisture content was developed using non-linear regression techniques. On extrapolation to higher wind speeds (> 10 km h^{-1} at 1.5 m in the forest) the model is apt to over predict which, from a fire controller's viewpoint, is more desirable than one which under predicts. It is possible that the relationship between rate of spread and wind speed is a sigmoidal one; further studies of the behaviour of fires under extreme conditions are needed to confirm this.

Flame size, although difficult to measure accurately, was directly related to rate of spread and fuel quantity. Fire intensity and flame length were related by a power function but the model coefficients were significantly different to those reported by Byram (1959). It is likely that model coefficients vary between fuel types so flame length is not a reliable estimator of fire intensity when comparing fires in different fuels.

Figure 8–23: Flame residence time calculated from rate of spread and flame depth with fuel quantity consumed. No intercept model is also graphed.



CHAPTER 9

FIRE IMPACTS RELEVANT TO JARRAH FOREST MANAGEMENT: AN OVERVIEW

9.1 Introduction

Previous chapters describe the experimental modelling of fire behaviour. These models enable fire behaviour predictions to be made in terms which convey information about the difficulty of suppression or the damage potential of the fire, such as rates of spread, flame dimensions, flame residence time and intensity.

When planning, implementing and evaluating prescribed fires, estimating the impact of wildfires, or studying fire effects, it is important to be able to identify and measure variables which are linked to the acute impacts of fire on vegetation and soils, (e.g., Ryan and Noste 1985, Wade 1987 and Wade and Lundsford 1990). In reviewing the effects of fire on small vertebrates, Friend (1993) used the definition of acute impact provided by Warren *et al.* (1987), which incorporated immediate physical impacts during the combustion phase and up until the time vegetative re-growth began, which could be several months after the fire. Acute impacts are defined in this thesis as the physical impacts of fire on vegetation and soil imparted during the flaming and smouldering phases of combustion. For jarrah forest fuels, most acute impacts occur over 1-2 minutes during the passage of flames, although stem damage to trees can occur over longer periods when large woody fuels burn near the tree.

As well as describing fires for interpreting ecological effects, it is equally important to be able to link fire variables, factors affecting heat transfer and acute impacts so that managed fire can be effectively and reliably applied to achieve a desired ecological outcome. Managing fire in jarrah (*Eucalyptus marginata*) forests of south-west Western Australia includes prescribing fires to reduce fuel levels without damaging the boles and crowns of trees and prescribing fires to regenerate or eradicate specific plant species (see Chapter 1).

Although acute impacts give rise to ecological responses, fire ecologists have generally displayed indifference to how fires actually produce their ecological effects (Van Wagner and Methven 1978, Johnson 1992). McArthur and Cheney (1966) noted that in a literature review of fire effects by Hare (1961) there was an absence of a precise description of the type of fire causing the effects. Alexander (1982) reported that this trend had continued in spite of advances in the science of fire behaviour. In attempting to redress this situation, Tolhurst (1992 unpublished report) provided a list of ecosystem components and a corresponding list of what he felt were important fire variables affecting their response to fire.

There are few quantitative links between fire behaviour variables and acute impacts. Van Wagner (1973) developed a model for predicting height of crown scorch from fire intensity (see chapter 10), and scorch height and tree mortality relationships have been developed for some tree species (e.g., Van Wagner 1970b, Methven 1971, Dieterich 1979 and Bevins 1980). Peterson and Ryan (1986) have produced a comprehensive model for predicting the probability of mortality in conifers after fire. Their model incorporates heat transfer theory as well as experimentally derived relationships to predict mortality due to crown scorch and cambial death.

It is unlikely that the acute impacts of fire will be modelled from first principles in the foreseeable future for several reasons. Firstly, combustion and heat transfer are separate processes, both of which are complex and poorly understood. Secondly, there is limited information linking fire behaviour variables with acute impacts, an exception being the linkage between fire intensity, flame dimensions and scorch height (e.g. Van Wagner 1973, Luke and McArthur 1978, Cheney *et al.* 1992). Thirdly, ecosystem responses will depend on numerous other interrelating factors including climate, landform and soils, the fire regime, (Gill 1977 and 1981), fire size, patchiness, the ecological and biological characteristics of the ecosystem.

Therefore, in the absence of universal physical models, empirical or semi-empirical models which predict acute impacts from readily measured fire behaviour variables and heat transfer factors will need to be developed, or existing ones validated for each vegetation type or fuel complex, including the jarrah forest.

The way in which an organism responds to fire will depend largely on its life cycle, its fire adaptations, and on the fire regime (Gill 1977 and 1981). Fire regime is defined as the cumulative effects of fire frequency, fire season, fire type and fire intensity (Gill 1981). By this definition, fire intensity is a generic term describing the characteristics of the fire which cause physical or acute impacts to the forest biota; impacts which give rise to physical damage and biological effects. Interpreting immediate and longer term fire effects requires both an understanding of the relevant processes and correct description of the fire (McArthur and Cheney 1966, Gilmour and Cheney 1968, Muraro 1971, Methven 1978, Alexander 1982).

Byram's (1959) fire intensity, even with its limitations (Tangren 1976 and Cheney 1990a), is the most commonly used and most meaningful expression that describes a fire in terms of its potential to damage vegetation. Fire intensity relates well to the impact of fire on plant tissue above the flames (McArthur and Cheney 1966, Van Wagner 1973, Methven 1978, Alexander

1982, Trollope 1983, Trollope and Tainton 1986, Van Wilgen *et al.* 1990), but does not relate well to impact within the flames or in the soil which is largely a function of fire duration (e.g., Wells *et al.* 1979, Knight 1981, Frandsen and Ryan 1986). Fire intensity has little meaning if there is significant after-burn or combustion behind the flaming zone (Tangren 1976, Armour *et al.* 1984, Engle *et al.* 1989). This is likely to occur in compacted fuel beds or where the fuel complex consists of a range of various particle sizes.

Several models have been developed for predicting the height of scorch to above ground vegetation from fire intensity (Van Wagner 1973, Luke and McArthur 1978, Trollope and Tainton 1986, and Cheney *et al.* 1992). Gill *et al.* (1986a) and Luke and McArthur (1978) provide information on the likely level of damage to trees from fires of various intensity ranges and Bradstock and Myerscough (1988) reported a direct relationship between fire intensity and mortality in populations of *Banksia serrata* and *Isopogon anemonifolius*. Reinhardt and Ryan (1988) have prepared nomograms relating flame length, fire intensity and scorch height to estimate tree mortality resulting from prescribed fires for a variety of North American tree species. Wade (1988) published a very useful guide for prescribed burning in the south eastern states of the U.S. which examines some of the ecological impacts of fire as well as fire behaviour prediction and application. Ryan and Steele (1989) have made advances in predicting cambium mortality resulting from broadcast burning in mixed conifer shelterwoods from bark thickness and quantity of log fuel and a substantial amount of research has recently linked morphological damage or injury to plant mortality (e.g. Ryan 1982a, Ryan 1982b, Ryan *et al.* 1988, Ryan and Reinhardt 1988, and Reinhardt and Ryan 1988). Ryan and Noste (1985) presented a preliminary method for evaluating fire severity based on flame length and the depth of char, or degree of fuel consumption.

9.2 Acute impacts of fire

The severity of acute impact varies considerably from one fire circumstance to another, but the general nature of acute impacts includes;

i) reduction or removal of live and dead vegetation resulting in changes in cover, structure and habitat to varying degrees,

ii) some plant and animal death and injury and,

iii) soil heating and subsequent effects on soil chemistry, structure and various soil borne organisms.

Acute impacts on the vegetation equates to an almost instantaneous change in habitat (food, shelter and breeding sites), particularly if the fire is intense. Thus, the impact on fauna will depend on habitat requirements, the extent to which these have been affected by the fire, on the rate of recovery of vegetation and on the biology of various taxa (e.g. see review by Christensen and Abbott 1989, and Friend 1993). Therefore, measuring the impact of fire on vegetation is the key to interpreting fire impact on fauna.

The extent or severity of acute impact on an ecosystem will depend on the amount and rate of heat energy released and on the amount and rate of heat transfer to plants and the soil. Flames are the essence of a bushfire. Flame temperature *per se* does not necessarily relate to the amount of heat given off as temperature is a measure of the degree of hotness while heat is the quantification of the work transferred from a warm body to a cool body. However, the temperature history experienced by plant tissues does relate to thermal death time (e.g., Hare 1961, Wright 1970, Ryan 1982b and Engle *et al.* 1989) so intuitively relates to the threat posed by fire to plant tissue.

It is therefore important to measure and describe the fire and factors affecting heat transfer in terms which best reflect or characterise the temperature histories experienced by plant tissue and the soil at critical locations. Fire ecologists have attempted to measure temperature histories in the field to characterise fire intensity but this has met with mixed success mainly because of the high degree of temporal and spatial variation in temperature (e.g., see Hobbs and Atkins 1988, Cheney *et al.* 1992). There are also practical difficulties with using this technique beyond small, intensively monitored experimental fires. However, thermocouple temperature histories can be a useful means of correlating temperature histories with meaningful and more easily measurable fire descriptors. The use of thermocouple temperature histories in characterising fires in jarrah forest litter is described in Chapter 11.

A framework is presented in this chapter for describing the acute impacts of jarrah forest fires which give rise to physical damage and to ecological responses (Figure 9-1). Subsequent chapters deal with modelling these impacts from experimental data. The notion is that temperature history, therefore the acute impacts of fire, are related to fire behaviour variables which reflect heat output, and to factors affecting heat transfer; variables which are more readily measurable in the field than temperature histories.

9.3 Acute impact zones

In discussing tree damage resulting from prescribed fires, Ryan (1982a, 1990) separated damage to the tree crown, bole and roots. Similarly, Wade (1987) recommended using Byram's (1959) measure of fire intensity for correlating with fire effects above the flaming zone, reaction intensity and residence time for flame impact, and heat per unit area or depth of burn for estimating below ground effects. These approaches recognize that each organ is affected by different aspects of heat transfer which are linked with different measures of fire behaviour. The experiments described in the following chapters examine the physical impact of fire on the jarrah forest in three zones (impact zones); above the flames, in the flames and below the flames. A framework for investigating acute impacts relevant to current and foreseeable fire management of jarrah forests is illustrated in Figure 9-1 and further described in Table 9-1. Key elements of this framework are;

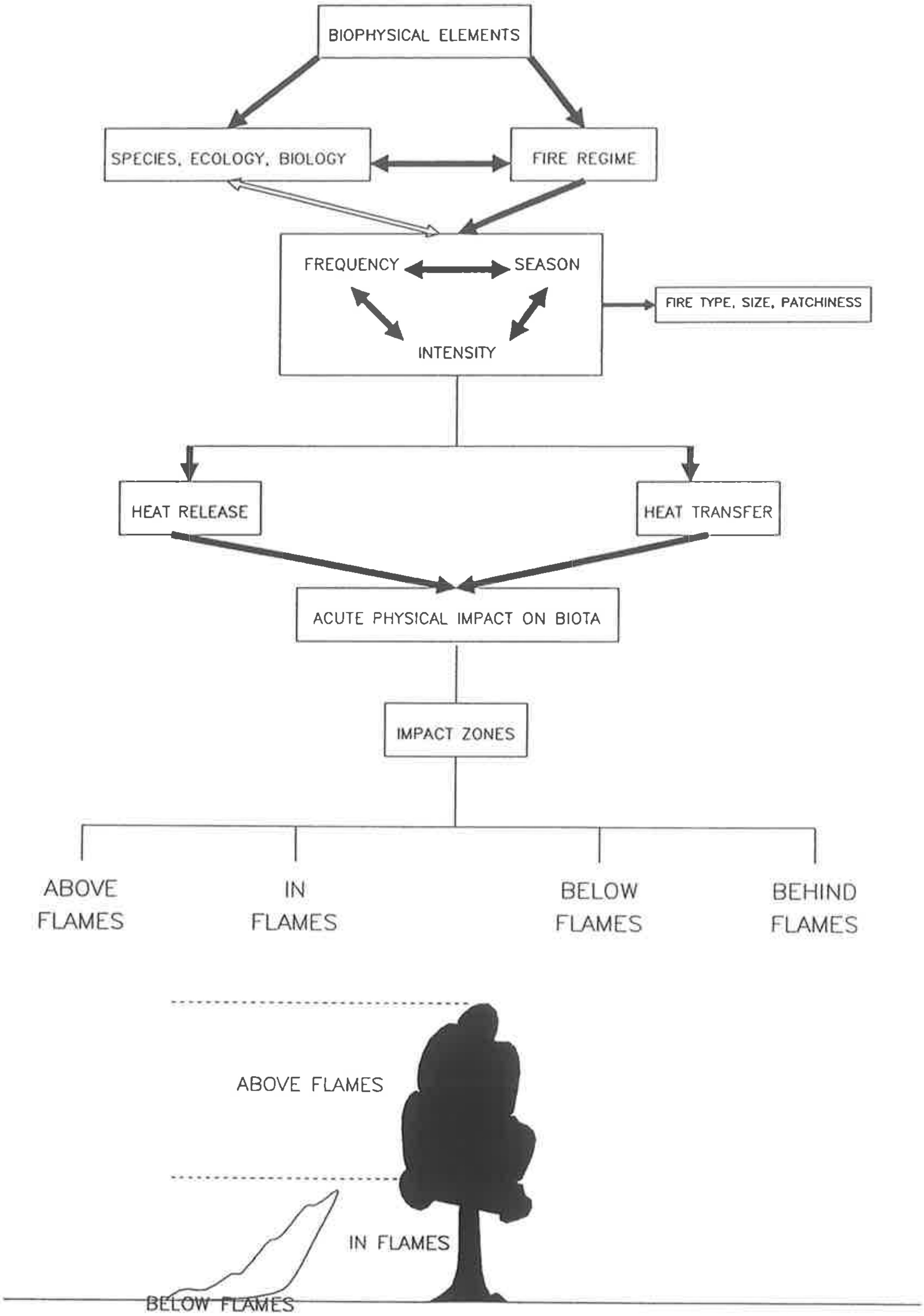
i) stratification of the area within and around the combustion zone,
ii) identification of important physical impacts within these strata,
iii) identification of factors that are likely to effect heat transfer to plants and soil and,
iv) seeking correlations between "easily measured" fire variables, variables which are likely to effect heat transfer, and the impacts.

9.3.1 Impact zone above the flames

This zone is affected by hot (but not burning) turbulent gasses rising above the flames. The most obvious impact in this zone is crown scorch or leaf browning as leaves, fine twigs and fruits experience a lethal time-temperature regime. For most species in the jarrah forest this leads to crown replacement but in other forests plants may be killed outright by full crown scorch (e.g. *Pinus radiata*). The result is a reduction in cover and density of vegetation and often massive and synchronised seed release.

Byram's (1959) fire intensity and flame characteristics, particularly flame height and flame length, are the most commonly used measures for predicting the height at which lethal temperatures (lethal to leaves and fine twigs) occur in this zone because flame size reflects the amount of heat being given off (fire intensity). The amount of heat transferred to vegetation above the flames is also affected by ambient temperature and wind speed. Semi-empirical models for predicting scorch height (e.g., Van Wagner 1973, Cheney *et al.* 1992) incorporate wind speed and ambient temperature as factors which affect scorch height independent of the

Figure 9–1: Acute fire impacts linkages.



effects of these factors on fire behaviour. Chapter 10 evaluates the performance of Van Wagner's crown scorch model and describes the experimental development of models to predict crown scorch height in jarrah forests.

Table 9-1: Impact zones, impacts, quantifying impacts, descriptors of heat output and factors affecting heat transfer.

IMPACT ZONES

	Above Flames	In flames	Below flames
Impacts	Scorch and death of leaves, twigs, fruits leading to defoliation, seedfall, cover reduction	Defoliation, mortality, cambial damage, bark loss, soil exposure, seedbed prep., seedfall, seed mortality	Soil heating, seed germination, soil chemical and structural changes, micro-organisms
Measure of impacts	Scorch height, scorch area, cover, density, quantity of seedfall	Defoliation height, area defoliated, mortality by species, area of cambium damaged, cover, structure, depth of burn, quantity of fuel burnt	Soil temperatures, chemical changes, bulk density, colour, soil seed germination
Descriptors of heat output	Flame height, flame length, Byram intensity	Flame height, flame depth, flame residence , time intensity, combustion rate, fuel consumed	Fuel consumed, fuel size, fuel moisture, flame residence time
Factors affecting heat transfer	Temperature, wind speed, height above flames	Bark thickness, stem size, plant moisture content, bark moisture, ambient temperature, drought index	Soil moisture content, soil bulk density, drought index

9.3.2 Impact zone in the flames

In this zone, plants are killed either by defoliation (incineration) or by stem girdling at or near ground level. Defoliation height approximates the height of the flames when flame height is less than the height of the vegetation. The extent of defoliation will be affected by factors affecting fire intensity and by the moisture content of live vegetation. Most understorey species in the jarrah forest have thin bark and are readily girdled and killed to ground level by even the mildest of fires (most re-sprout from subterranean organs). Tree and lower tree species which develop thick protective bark are more resistant to death by thermal girdling. Stem mortality will depend on bark thickness, bark moisture content, and the temperatures and duration of heating experienced at the bark surface. Chapter 11 describes both laboratory and field experiments aimed at linking fire behaviour variables, factors affecting heat transfer and some important impacts in the flaming zone.

9.3.3 Impact zone below the flames

This zone is the top 2-3 cm of soil, including the soil surface. The level of fire-caused impact on the soil will depend on how much of the fuel resting on the soil is consumed, how dry the fuel is and the thermal properties of the soil, such as moisture content and bulk density (see Aston and Gill 1976). Soil heating is independent of intensity, although intensity may reflect fuel consumption. The extent to which the soil is heated will affect the survival of fine roots and lignotubers, and affect seed bed preparation, germination of soil stored seed, micro-organism responses and the chemistry and structure of the soil. When fuels and the soil are moist and there is only partial combustion of the litter bed, then top soil is unlikely to be affected. The physical process of heat transfer through soil and some effects of fire on soil are summarised by Aston and Gill (1976), Wells *et al.* (1979), and Humphreys and Craig (1981).

9.4 Concluding discussion

Jarrah forests are managed for many purposes, but whatever the purpose, sound management of fire is fundamental to achieving objectives. A firm scientific knowledge of fire behaviour is necessary for implementing wildfire control strategies and for setting prescribed fires. Fire managers also need to be able to evaluate and to predict both the commercial and ecological consequences of planned and unplanned fires. This requires an understanding of fire-induced physical impact on the vegetation and on the soil. Acute fire impacts give rise to commercial impacts and to ecological responses.

The following chapters describe the experimental development of some important fire impact models which couple fire behaviour variables, factors affecting heat transfer and acute physical fire impacts.

CHAPTER 10

FIRE IMPACT ABOVE THE FLAMES: CROWN SCORCH

10.1 Introduction

Fire kills or damages vegetation by either girdling or incinerating the stem or by incinerating or scorching foliage and buds. Crown or canopy scorch is usually considered to be an undesirable effect of fire, especially in coniferous forests where excessive crown scorch leads to tree death (e.g. Van Wagner 1970, de Ronde 1983, Wade and Johansen 1986, Wade 1988, Weise *et al.* 1989 and Johnson 1992) or loss of wood production (Hodgson and Hieslers 1972 and Kellas *et al.* 1984). For fire sensitive North American coniferous forests, the degree of crown scorch is widely used to predict mortality (e.g., Peterson 1985, Peterson and Ryan 1986, Reinhardt and Ryan 1988, Saveland and Neuenschwander 1990, Swezy and Agee 1991, Finney and Martin 1993). However, jarrah and marri, like many species of *Eucalyptus*, have evolved adaptive traits to recover or regenerate following fire-caused injury (Jacobs 1955 and Gill 1978) and quickly replace scorched crowns from epicormic shoots.

In the fire management of jarrah forests, scorch height, or the height to which foliage and fine branches have experienced a lethal temperature regime, is often used as a criterion for implementing prescribed burns (Sneeuwjagt and Peet 1985). When setting fuel reduction burns, the aim is to minimise crown damage by keeping scorch height to less than 6 m. Scorch above this level can cause long term crown and stem damage especially to small saplings where growing tips can be killed back and deformities induced. Full crown scorch can cause a temporary reduction of amenity value and can disrupt breeding birds and arboreal mammals which utilise hollows or feed in the green canopy (Christensen *et al.* 1988 and Inions *et al.* 1989). The protection benefits derived from fuel reduction burning can be reduced if the forest canopy is fully scorched. Scorch induces leaf fall which can add up to 5 t ha^{-1} of additional fuel to the forest floor (Luke and McArthur 1978).

In some circumstances however, the objective of prescribed burning is to induce full scorch to the forest canopy. This may be required to maximise regeneration by creating "ashbed" and by stimulating a massive and synchronised release of canopy stored seed (e.g. see Cremer 1965, Henry and Florence 1966, Christensen 1971 and Burrows *et al.* 1990), to induce a positive growth response from established trees following crown replacement (Podger and Peet 1965 and Kimber 1978) and to interrupt the life cycle of forests pests such as jarrah leaf miner (Abbott *et* *al.* 1993). Prescribed burns to regenerate or eradicate specific understorey species usually require fires of sufficient intensity to cause full crown scorch (e.g., see Shea *et al.* 1979 and Burrows 1985).

Whatever the purpose of prescribed burning, it is essential that jarrah forest fire managers be able to predict the extent of crown scorch. Sneeuwjagt and Peet (1985) present a table for predicting the maximum scorch height to jarrah and pine forests during low intensity spring fires from rates of spread and total available fuel quantities. During autumn conditions, scorch height is estimated to be 1.8 times greater than the predicted spring scorch height. The table presented by Sneeuwjagt and Peet (1985) applies to a narrow range of burning conditions which is adequate for low intensity fuel reduction fires where rates of spread are less than about 70 mh^{-1} and scorch height are less than 12 m. A rule of thumb used in south-eastern Australian eucalypt forests is that scorch height is about six times flame height (Luke and McArthur 1978). Hoare (1985) used flame height to assess and predict the biological effects of fire in tropical eucalypt woodland and found scorch height to be about 4 times flame height.

During a forest fire, vegetation above the flames is affected by a rising plume of hot air. The crowns of most plant species will be scorched and killed when leaves and fine branches are heated above a temperature of 60-70 ^{o}C (e.g., Byram 1948, Kayll 1968, Methven 1971, Ryan 1982b, Cheney *et al.* 1992). Thomas (1963), using dimensional analysis, derived a relationship between temperature rise above ambient, fire intensity and the height above ground for no wind situations. Van Wagner (1973) used this relationship as a basis for determining the height at which lethal temperatures were experienced (scorch height). He also introduced the idea that, under the influence of wind, the plume follows an angled path up into the vegetation. His relationship between scorch height and fire intensity was developed from 13 small experimental fires in Canadian forest types with theoretical adjustments to scorch for ambient temperature and wind speed; the theory being that scorch height is directly related to ambient temperature and inversely related to wind speed, *ceteris paribus*. This embodies the concepts described in Chapter 9 above; the acute physical impact of fire is a function of the amount and rate of heat release (intensity) and of factors affecting heat transfer (ambient temperature and wind speed). Van Wagner's (1973) equations are shown below (in the units of this study).

$$h_s = 0.148(I)^{2/3}$$

$$h_s = \frac{0.742(I)^{7/6}}{[0.0256(I) + (0.278U)^3]^{1/2} \quad (60-T_A)}$$ (Van Wagner 1973),

where h_s = scorch height (m), I = fire intensity (kW m^{-1}), U = wind speed (km h^{-1} in the forest at 1-2 m) and T_A = ambient temperature (^{o}C).

Van Wagner's models have been widely used to predict crown scorch and tree mortality in North American conifer forests (e.g., Rothermel and Deeming 1980 and Kercher and Axelrod 1984). Cheney *et al.* (1992) developed a semi-physical model based on Van Wagner's model to predict scorch height from low intensity fires in *Eucalyptus sieberi* regrowth forests in New South Wales. They found that most variation in scorch height (S_h) (55%) could be explained by flame height, followed by fire intensity and rate of spread. As fuel quantity was considered to be more or less constant during their experimental fires, they presented a model for predicting scorch height from rate of spread (r), and ambient temperature (T);

$S_h = 2.9263(R^{0.5})(e^{0.0537T})$ (Cheney *et al.* 1992)

To develop a physical model of scorch height, Cheney *et al.* (1992) measured radiation and air temperature in the crown scorch zone above low intensity prescribed fires in *Eucalyptus sieberi* regrowth forests. They used these measurements and Van Wagner's plume theory to model plume temperatures above fire and combined this with a model describing the thermal response of *E. sieberi* leaves to produce a model to predict scorch height.

None of the physical models described have been validated for jarrah forests and the scorch tables presented by Sneeuwjagt and Peet (1985) are limited in that they only apply to low intensity fires. The aim of the experiment described in this chapter was to test the performance of these models in jarrah forests and, if necessary, develop a better model for predicting scorch height in jarrah forests over a wide range of burning conditions.

10.2 Methods

The study was carried out in conjunction with the summer and early autumn fire behaviour studies described in Chapter 8. Fuel and fire behaviour data were gathered from the 20 m x 4 m belt quadrats or sample cells described in Chapter 8 and the mean monthly moisture content of the dead outer bark (outer 5-10 mm) of jarrah trees was determined from weekly samples from 10 trees (as described in Chapter 8). Average scorch heights within these cells were measured 5-6 weeks after fire using either a 2 m height stick or a clinometer. These measures were regressed with mean fire behaviour and fuels data obtained for the sample cell (see Chapter 8). Scorch height measurement was limited by the maximum height of the vegetation at each sample point. In many cases, the entire vegetation profile was scorched indicating that the potential scorch height exceeded the height of the vegetation used to measure scorch height. Therefore, only data where scorch height was less than canopy height were used in analysis.

Additional scorch height data were acquired from George Peet (unpublished data archived at the CALM Manjimup Research Station Archive File 22/06.2). Peet's data were obtained during small, low intensity fires set in jarrah forests in spring and mid-autumn 1966 when conditions were cool and moist (SDI < 800 compared with SDI > 1000 for the summer/early autumn experimental fires described in Chapter 8). Seasonal data were analysed separately because of seasonal differences in weather, fuel moisture content and tree physiology.

10.3 Results and Discussion

10.3.1 Scorch height and semi-physical models

Observed scorch heights are graphed with scorch heights predicted by Van Wagner's (1973) model using fire intensity, ambient air temperature and wind speed in Figure 10-1. When applied to jarrah forests, Van Wagner's model consistently under predicted scorch height. The scorch model derived by Cheney *et al.* (1992) also under predicted at low scorch levels and showed poor predictive capacity at high fire intensities. Differences in forest type, fuel characteristics and methods of calculating fire intensity probably explains the poor performance of these models, suggesting that the models do not include all variables affecting scorch, so do not have universal application. Cheney (1990a) pointed out the difficulties with using Byram's fire intensity to quantify and compare fires in different fuel types. Correction factors to improve the predictability of the Van Wagner model were generated by regressing observed scorch height with predictions, as shown in Figure 10-1. Regression analysis solving for coefficient values ("k" values) using Van Wagner's model did not improve the R^2 value.

The best-fit equation (Equation 10-1) for predicting scorch in jarrah forests from fire intensity, ambient temperature and wind speed using Van Wagner's (1973) equation form is;

$$S_h = 1.49 \left[\frac{0.742\,(I)^{7/6}}{(60 - T_A)\,[0.0256(I) + (0.278U)^3]^{1/2}} \right] + 1.06 \qquad R^2 = 0.65$$

(Equation 10-1)

where S_h = scorch height in jarrah forests (m), I = fire intensity (kWm^{-1}), T_A = ambient air temperature (^{o}C) and U = wind speed in the forest and at 1.5 m ($km\ h^{-1}$).

Plate 10-1: Low scorch height (<6m) resulting from low intensity fuel reduction burn (150 kWm^{-1}).

Plate 10-2: High scorch height (20 m) resulting from a moderate intensity (1,000 kWm^{-1}) summer fire.

Plate 10-3: Canopy resprouting from epicormic shoots 6 months after a fire which fully scorched the canopy.

Figure 10–1: Scorch heights observed following fires in jarrah forests graphed with scorch heights predicted from fire intensity, temperature and wind speed using Van Wagner (1973).

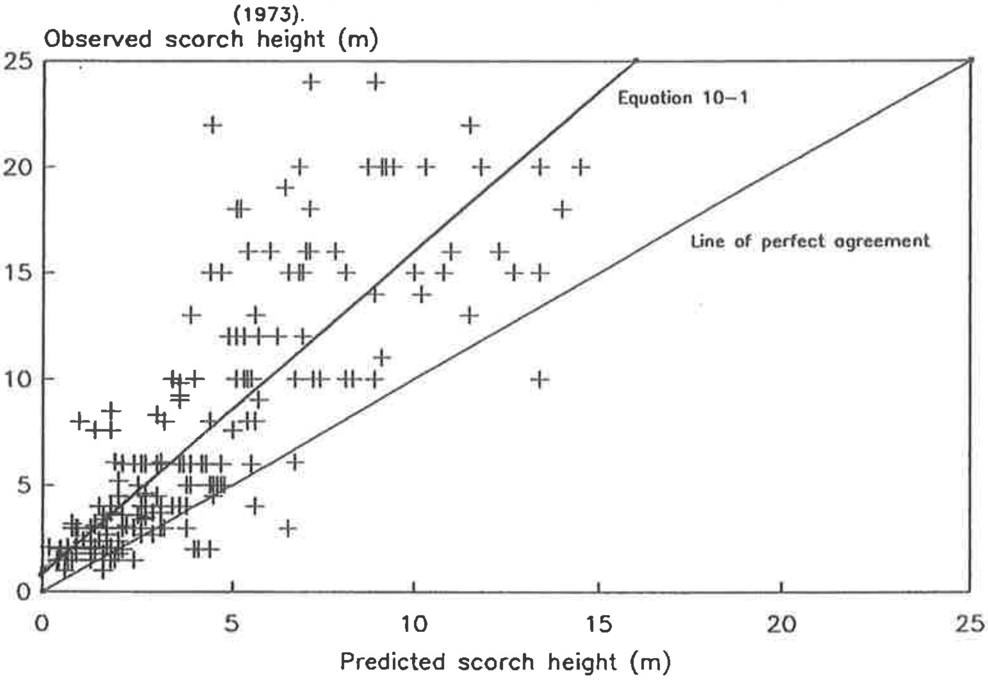
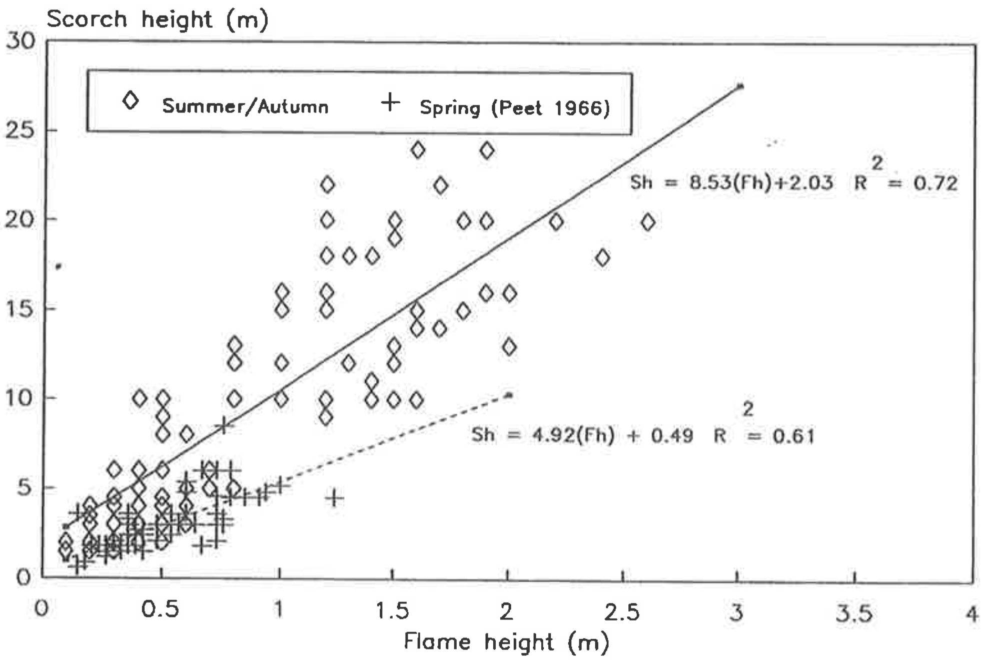


Figure 10–2: Scorch height with flame height for jarrah fires in different seasons. Spring data are from Peet (1966 unpubl.)



10.3.2 Scorch height and fire behaviour variables

Of the fire behaviour variables, flame height, flame length and Byram's fire intensity showed strongest correlation with scorch height (Table 10-1 below). This is not surprising as these descriptors reflect the amount and rate of heat release. There is a considerable amount of variation in scorch height not explained by the relationships in Table 10-1 which reflects the inherent variability and difficulty of measurement of scorch height, fire behaviour, fuels and meteorological conditions. In some instances, tilting of the convection column would have resulted in inaccuracies when matching scorch height with the appropriate fuel and fire behaviour variables which gave rise to the scorch, further adding to the unexplained variation in scorch height. There were also clear seasonal influences as described by the linear regressions below and graphed in Figure 10-2. Scorch height during warm, dry summer/autumn conditions was about 9 times flame height and during spring conditions, about 5.6 times flame height, as determined from regressions through the origin. Predicting scorch height for all seasons using flame height was significantly improved by including ambient temperature in the equation (Table 1).

Table 10-1: Equations and associated statistics for predicting scorch heights (S_h) (m) in different seasons (summer = summer/autumn) from flame height (H_f) (m), flame length (L) (m), ambient temperature (T_A) (°C) and fire intensity (I) (kW m^{-1}). Spring equations were derived from George Peet's (1966) unpublished data. Standard errors are shown in parentheses. Residual = predicted - observed.

Equation	Season	N	R^2	Residual statistics Mean	Range
$S_h = 15.36(h_F)^{0.8}\ e^{TA(-0.013)}$ (3.39) (0.05) (0.008)	Spring, summer	164	0.74	0.09	-5.5 to 9.3
$S_h = 4.92(hF)+0.49$ (0.29) (0.15)	Spring	50	0.61	0.00	-2.1 to 4.3
$S_h = 8.53(hF)+2.03$ (0.49) (0.55)	Summer	114	0.72	0.00	-6.1 to 10.2
$S_h = 5.87(L)+2.81$ (0.33) (0.53)	Summer	114	0.71	0.00	-8.4 to 10.9
$S_h = 0.36(I)^{0.59}$ (0.12) (0.05)	Summer	114	0.58	-0.11	-10.3 to 13.8
$S_h = 0.28(I)^{0.58}$ (0.09) (0.06)	Spring	50	0.59	0.01	-2.4 to 4.7

Higher scorch levels experienced during summer and early autumn fires (Figure 10-2) are probably due to;

i) higher ambient air temperatures in summer and early autumn,

ii) increased susceptibility of plants to scorching due to a significant water deficit over the hot, dry summer months (Van Wagner 1973, see Crombie *et al.* 1988 for water deficit),

iii) combustion of additional fuels which do not normally burn under cool, moist spring conditions. These include live vegetation, coarse dead fuels (logs etc., see Burrows 1985) and bark on the boles and limbs of standing live trees. Coarse fuels and bark are not included in the calculation of fire intensity.

The seasonal variation in the moisture content of dead outer bark on jarrah trees is graphed in Figure 10-3. During spring fires the moist bark rarely ignites or chars beyond flame height, however in summer and early autumn when the bark is dry, combustion of bark along parts of, and in some instances the entire length, of the bole were observed, especially during higher intensity fires. As well as augmenting spot fires (fires which start ahead of the main fire from fire brands), heat released from bark burning on the stem and branches in or near the canopy contributes to crown scorching. The combustion of coarse surface fuels (logs and limbs) and of bark on standing trees is not included in the quantity of fuel burnt when calculating fire intensity. The quantity of bark burnt is difficult to measure and varies with fire history, but in jarrah forest fires it has been estimated to be as high as 6 t ha^{-1} (Peet and McCormick 1965b, Ward and Burrows 1985 unpubl.).

Byram's fire intensity is a useful measure of a fire's damage potential, as discussed above in Chapter 9. Scorch heights experienced during summer and early autumn fires ("dry fires") were related to Byram's fire intensity by the equation shown in Table 10-1 above which is graphed with Van Wagner's (1973) relationship in Figure 10-4. A similar equation was derived using Peet's unpublished data for spring fires ("moist fires"). All equations are of the same form, but the equations derived for jarrah forest fires predict a higher scorch level than Van Wagner's equation, especially under summer/autumn conditions (Figure 10-4). The explanation provided above for the discrepancy between the predictions made by Van Wagner's semi-physical model and observed data probably explains the under-prediction. For these reasons, scorch height predictive models developed under one set of forest and fuel conditions may not be transferable to other conditions and unique equation coefficients may need to be generated for each forest/fuel type.

Figure 10-3: Mean monthly moisture content of the outer bark of jarrah.

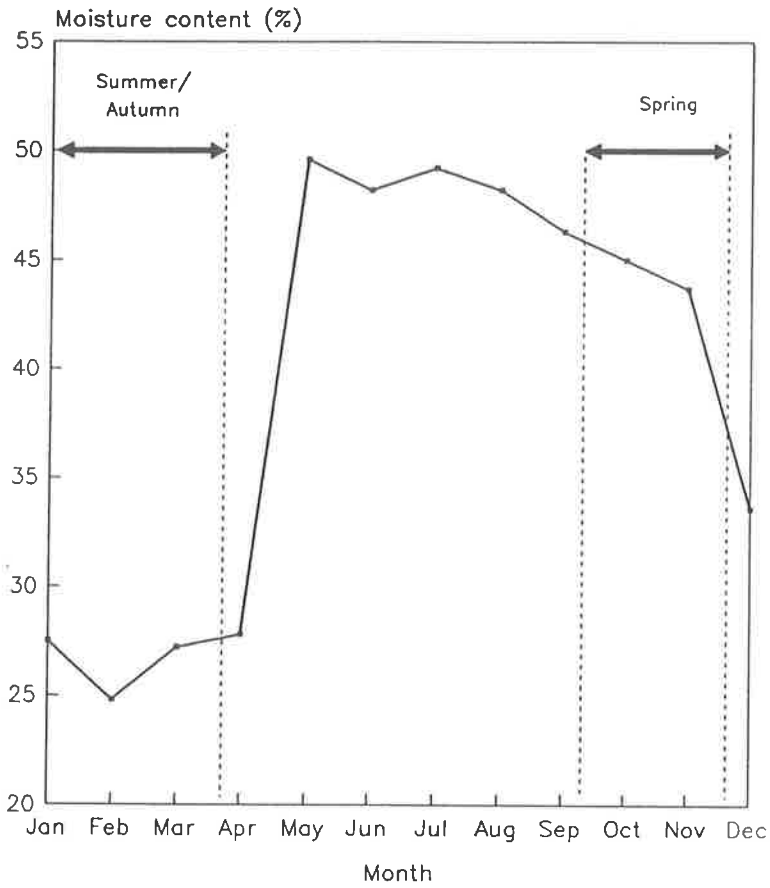
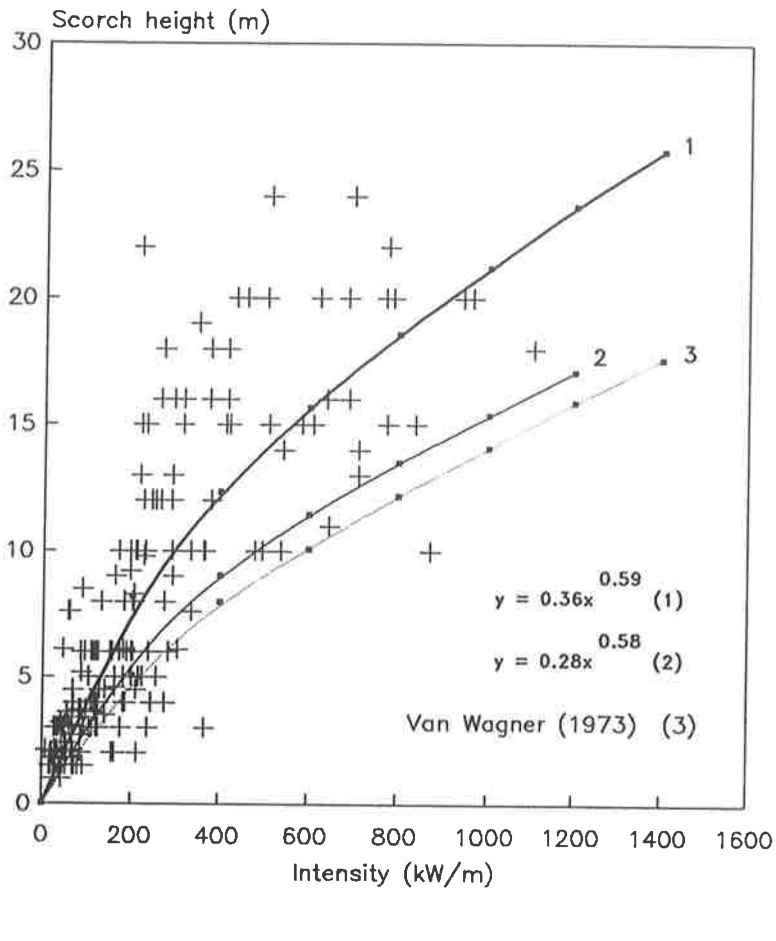


Figure 10-4: Scorch heights experienced during jarrah forest fires in summer/autumn (1) and spring (2) with Byram's fire intensity. Scorch height predicted using Van Wagner's (1973) model (3) also graphed.



10.4 Management implications

Flame height, flame length and fire intensity are convenient and meaningful fire behaviour descriptors for predicting scorch height. These fire behaviour variables are dependent on fire rate of spread and the quantity of fuel burnt (see Chapter 8), which can be controlled, within limits, when implementing prescribed fires.

An important fire management objective in jarrah forests is to protect human life and property and forest values from the impacts of intense summer wildfires (see Chapter 3). A strategy for achieving this is to implement low intensity fires under cool, moist conditions in spring. This operation successfully achieves fuel reduction whilst minimising canopy damage, especially in regrowth forests. Current prescriptions require scorch height to be less than 6 m which also minimises the impact on flora (especially small trees), fauna and visual qualities. Using the relationships contained in Table 10-1, this can be achieved by prescribing fires with flame heights less than about 1 m in spring and less than 0.5 m in summer/autumn, or maintaining fire intensities below about 250 kWm^{-1}. For a standard jarrah forest fuel with about 8.0 t ha^{-1} of available fine fuel, headfire rates of spread should be less than about 65 m h^{-1}.

Wildfires or prescribed fires burning under dry soil and fuel conditions in summer or autumn (i.e. when the SDI > about 1,000) cause significantly higher crown scorch for given fire behaviour conditions (flame size and fire intensity) than spring fires. Where the aim is to fully scorch the forest canopy with prescribed fire, then this is best achieved with the minimum fire intensity needed to fully scorch the canopy to ensure that the fire is controlled and does not cause excessive damage to other forest values. From the relationships in Table 10-1, the minimum flame height to achieve full canopy scorch to a mature jarrah forest (top height 20-25 m) under warm, dry summer/autumn conditions is about 2-3 m which is equivalent to a fire intensity of about 1,000-1,200 kW m^{-1}.

10.5 Concluding discussion

Scorch height is an important physical impact which can have significant biological and commercial consequences. Although variable, it is a useful and meaningful criterion for setting limits to the intensity of prescribed burns and assessing the potential severity of wildfires so a capacity to predict scorch height is important for planning and implementing fire management activities. None of the existing physical models adequately predicts scorch height over the range of fire conditions likely to be experienced in the jarrah forest. This study developed new empirical relationships enabling scorch height in jarrah forest fires to be predicted, within reasonable limits, from readily measured fire behaviour variables such as flame height, flame length and fire intensity. The strong seasonal differences between these relationships is probably due to seasonal variation in i) weather conditions especially ambient temperature, ii) plant physiology and iii) fuels available for burning.

CHAPTER 11

FIRE IMPACT IN THE FLAMES: STEM DAMAGE

11.1 Introduction

Using prescribed fire to manage fuels or to "surgically" manipulate the vegetation, requires an understanding of fire behaviour and of the processes of heat transfer to the vegetation which give rise to acute impacts (see Chapter 9). The application of fire to reduce the abundance of *Banksia grandis*, a mid-canopy tree species highly susceptible to the soil borne pathogen *Phytophthora cinnamomi*, is an example of prescribing fire to engender a desirable acute impact (see Chapter 1). *Banksia grandis*, like most jarrah forest species, has the capacity to resprout from stem epicormics if the crown foliage is damaged, or from a subterranean lignotuber if the stem is killed (Burrows 1985). Jarrah is also a resprouter, but fire-caused damage can lead to timber degrade and significant economic losses (e.g., Greaves *et al.* 1965, McArthur 1967b, Peet and Williamson 1968, Wright and Grose 1970, Cheney and McArthur 1974, and McCaw 1983). It is therefore important that fire managers have the capacity to prescribe appropriate fires and be able to evaluate the impact of prescribed and wild fires on these species.

In the flaming zone, vegetation is physically damaged or killed either by defoliation or by stem girdling at or near ground level (Hare 1961, Gill 1974, Gill 1981, Ryan 1982b, Wade 1988). It is widely acknowledged that factors predisposing the cambium to injury are bark thickness, duration of heating and the thermal properties of the bark. Susceptibility to fire-caused injury decreases with increasing bark thickness and increases with duration of heating (e.g., Hare 1961, Kayll 1963, Spalt and Reifsnyder 1962, Martin 1963a and 1963b, Reifsnyder *et al.* 1967, Gill and Aston 1968, McArthur 1968b, Vines 1968, De Ronde 1982, Ryan 1982b, Ryan and Frandsen 1991 and Costa *et al.* 1991). There is some evidence that the physiological activity of the tree (transpiration and fluid movement in the vessels) may also modify cambial temperature during a fire (Hare 1961, Vines 1968, and Ryan and Frandsen 1991).

Bark thickness and thermal properties can be considered to be fixed for an individual plant during a forest fire. Fire resistance then, depends on the duration of heating, which will depend on the quantity of fuel burnt, its proximity to the plant, and fuel properties which affect combustion rate, such as particle size and arrangement and moisture content.

While there has been considerable research into the thermophysical process of heat transfer in tree boles, little of this work has translated into models which effectively link fuel properties and fire behaviour (factors affecting duration of heating), bark thickness and cambial injury. Tunstall *et al.* (1976) reported that maximum temperature on the leeward side of metal cylinders during grass fires was a linear function of rate of spread and flame height. Peterson and Ryan (1986) have produced a model to predict the probability of fire kill in conifer stands based on scorch height and cambial death derived from fire behaviour and stand characteristics. Ryan and Frandsen (1991) have also developed a useful model which predicts the probability of cambium mortality from duff depth and tree diameter for *Pinus ponderosa* forests. These relationship are unlikely to apply to the vastly different fuels and plants of the sclerophyllous jarrah forest.

The severity of fire impact on vegetation will depend on the temperature history experienced at the locale of interest. Temperature history relates to "thermal death time" (Wright 1970, Engle *et. al.* 1989), which intuitively relates to the threat posed by the fire to plant tissue. Numerous workers have examined the relationship between exposure time and temperature necessary to kill plant tissue (e.g. Martin 1963, Gates 1980, Levitt 1980, Wright and Bailey 1982). The accepted lethal temperature for most plant cells is 60^{o} C, but duration of heating is also important (Hare 1961). For example, Ryan (1982a) found that Douglas-fir (*Pseudotsuga menziesii*) seedlings can tolerate a temperature of 50 ^{o}C for 1 hour, 60 ^{o}C for 1 minute and 70 ^{o}C for 1 second.

Thermocouples have been used extensively to provide temperature histories of experimental fires in an effort to assist with understanding fire spread mechanisms (e.g. Davis and Martin 1960, Anderson 1964, Anderson *et al.* 1966, Rothermel and Anderson 1966, Van Wagner 1968a and others.). Fire ecologists have used time-temperature relationships to characterize fire behaviour for interpreting ecological responses, especially in heath and grasslands. Maximum temperature and the area beneath the temperature trace of sensors placed in the plant canopy and on the soil surface have been used as measures of fire intensity and of the vertical distribution of heat (e.g. Fahnestock and Hare 1964, Stinson and Wright 1969, Gill 1974, Bailey and Anderson 1980, Wright and Bailey 1982, Trollope 1983, 1984, Hobbs and Gimingham 1984, Engle *et al.* 1989, Stronach and McNaughton 1989). Thermocouples have also been used to assist with physical modelling of the thermal environment in tree boles during fires (e.g. Martin 1963b, Kayall 1963, Hare 1965, Vines 1968, Gill and Ashton 1968, Tunstall *et al.* 1976, de Ronde 1982, Ryan 1982, Ryan and Frandsen 1991 and Costa *et al.* 1991). The errors and limitations of measuring flame temperatures using thermocouples have been critically reviewed by many fire researchers (e.g., Breuer 1965a, 1965b, Walker and Stocks 1968, Rothermel and Anderson 1966, Van Wagner 1970, Vines 1981 and Alexander 1982).

In Australian eucalypt forests, Byram's fire intensity, flame dimensions and rate of spread have been widely used to characterise the severity of fire on vegetation in the flaming zone and to set limits for prescribed burning to minimise damage to trees (e.g., McArthur and Cheney 1966, Gill and Aston 1968, Vines 1968, Voutier and Sneeuwjagt 1971, Nicholls and Cheney 1974, Abbott and Loneragan 1983, Gill and Moore 1990 and Gill and Knight 1991). However, there is little statistical evidence directly relating these fire variables with mortality and damage to vegetation in the flaming zone. The link between these variables and damage is *a priori*, based on observation and field experience.

This chapter aims to determine the relative importance of fuel, fire behaviour (including fire intensity) and bark thickness on thermocouple temperature histories (hence injury to the cambium) in the flames and at various locales on *Banksia grandis* stems during laboratory fires. Temperature history is represented by maximum temperature and heat load (the area beneath the temperature history trace (degree minutes)). Readily measurable fuel and fire behaviour variables are examined for their usefulness as meaningful measures of temperature history, and ultimately, of damage potential in the flaming zone of jarrah forest fires.

11.2 Methods

Two experiments were conducted. The first experiment examined thermocouple temperature histories experienced in the flaming zone of laboratory fires described in Chapter 7, and sought statistical relationships with fuel and fire behaviour variables. The second experiment sought correlations between fire behaviour variables and temperature histories at the cambial layer of *Banksia grandis* stem sections during laboratory fires. The ensuing discussion also draws on the results of field investigations of fire-caused stem mortality and injury conducted by the author and published elsewhere (Burrows 1985, 1987).

11.2.1 Thermocouple temperature histories in the flaming zone

Thermocouples were used to measure the temperature history profiles in the flaming zone during the fire behaviour experiments conducted in the laboratory described in detail in chapter 7. Briefly, chromel-alumel wire thermocouples (30 gauge) were fixed on the fuel surface and at 10 cm above the fuel surface (see Figure 7-1, Chapter 7). Two sets of unshielded thermocouples were placed along the long axis of the fire table, at equal distances from the ends of the table and from each other. Thermocouples were linked to a multi-channel chart recorder which provided a trace of temperature with time. Each probe was read at 2 second intervals until thermocouple temperatures returned to within 5° C of ambient temperature. The area beneath each thermocouple temperature history trace was measured and called the "heat load" (H_L) (degree minutes). The fire laboratory facility and procedures for executing and monitoring the laboratory fires are described in detail in Chapter 7.

After each fire, all fuel residue was collected and weighed so that the quantity of fuel consumed by all forms of combustion (w_C) could be determined. As discussed in Chapters 6 and 7, the top 10-15 mm of litter bed are involved in the active combustion or flaming zone of wind driven laboratory fires. Fuel at depth was burnt in the secondary and glowing combustion phases. Without weighing devices, it was impossible to accurately determine the quantity of fuel consumed during the active combustion phase, so fire intensity was calculated using w_C.

Two measures of fire intensity were calculated;

i) Byram's (1959) fire intensity, $I = Hw_Cr$

ii) Combustion rate (Byram 1959 and McArthur and Cheney 1966), $C = Hw_C/t_R$,

where I = fire intensity (kW m^{-1}), C = combustion rate (kW m^{-2}), H = heat yield (18,700 kJ kg^{-1}), w_C = weight of fuel consumed (kg m^{-2}), r = flame rate of spread and t_R = flame residence time.

11.2.2 Thermocouple temperature histories at the cambium of bull banksia (*Banksia grandis*) during laboratory fires.

Experiments were conducted in the fire laboratory at Manjimup, described in Chapter 7. Peter Walsh, a Department of Conservation and Land Management technical assistant under my supervision, conducted the experiments and prepared a preliminary report (Walsh 1982 unpubl.). The methods employed by Peter Walsh were developed in consultation with me and are described below. In this section, I re-analyse the data from these experiments.

Jarrah forest litter fuel was collected from the field, prepared and weighed as described in Chapter 7, and spread evenly over the fire table. Fresh stem sections of *Banksia grandis*, about 40 cm in length and varying in diameter from 2 cm - 11 cm, were placed vertically into the fuel bed so that the base of the stem was resting on the asbestos base of the fire table. A single, freshly cut stem section was placed in the centre of the fire table for each experimental fire. Bark moisture content varied from 76% to 85% odw. Two 20 gauge chromel-alumel wire thermocouples were used to record temperature histories at the bark surface and at the cambial layer of each stem. Temperature history varies considerably around the bole of a tree during a fire (e.g., Gill 1974 and Costa *et al.* 1991). and significantly higher temperatures and larger flames have been reported on the leeward side of trees in the field (Fahnestock and Hare 1964 and Tunstall *et al.* 1976) and during experimental laboratory fires (Gill 1974). For a stem to be completely girdled by heat, it is essential that the cambium at the "coolest" portion of the circumference of the bole experience a lethal temperature regime, so the thermocouples were set on the windward side of each stem and slightly above the surface of the fuel bed. A thermocouple was installed at the cambial layer by carefully drilling a small hole into the stem from the leeward side to the cambium on the windward side. The thermocouple was inserted into the hole which was then sealed. Stem diameter (over bark) and bark thickness were measured at this location. Flame height, flame length, flame depth, flame residence time and rate of spread were measured for each experimental fire (as described in Chapter 7). The quantity of fuel consumed (oven dry weight) was determined by weighing fuel before and after each fire.

Plate 11-1: The temperature histories experienced at the bark surface and at the cambium of bull banksias stems were measured with thermocouples in controlled laboratory fires.

11.3 Results

Analysis of variance tables for all regressions are presented in Appendix 1.

11.3.1 Maximum temperatures in the flaming zone

Maximum thermocouple temperatures measured at the fuel surface were highly variable, so were not included in analysis. Temperatures recorded at 10 cm above the fuel bed in the flaming zone ranged from 493^{o} C to 988^{o} C for the 58 headfires examined. During fast spreading fires burning in light fuels, thermocouple temperature increased rapidly then decreased sharply with the passage of flames, resulting in a highly spiked temperature history trace.

Correlations between fuel and fire behaviour variables and temperature histories are shown in Table 11-1. The mean maximum thermocouple temperatures showed a significant linear relationship with flame length, flame height, Byram's fire intensity and rate of spread and a weak relationship with quantity of fuel consumed. Stronach and McNaughton (1989) found that maximum temperature during grass fires was linearly related to the quantity of fuel burnt.

Table 11-1: Pearson correlation coefficients for fuel and fire behaviour variables and thermocouple temperature histories measured in the flaming zone at 10 cm above the fuel bed.

Variable	Maximum Temperature	Heat Load
Quantity of fuel burnt (w_C)	0.47	0.81
Rate of spread (r)	0.65	0.07
Flame length (L)	0.74	0.42
Flame height (h_f)	0.71	0.51
Flame residence time (t_R)	0.29	0.40
Byram's intensity (I)	0.68	0.45
Combustion rate (C)	0.16	0.35

Figure 11–1: Maximum thermocouple temperatures in the flames and 10 cm above the fuel bed with rate of spread.

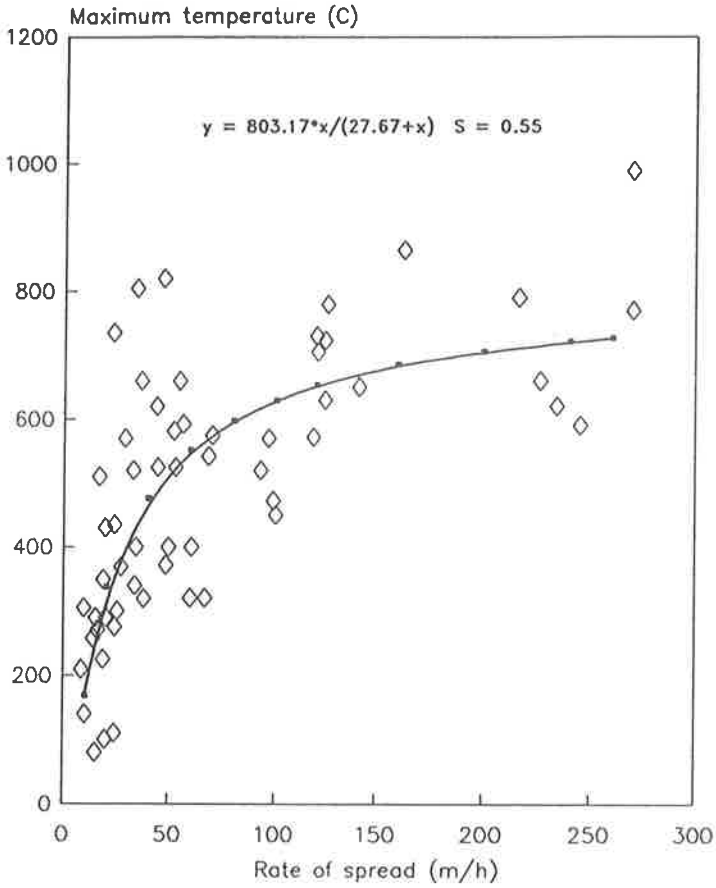


Figure 11–2: Maximum thermocouple temperature in the flames and 10 cm above the fuel bed with flame length.

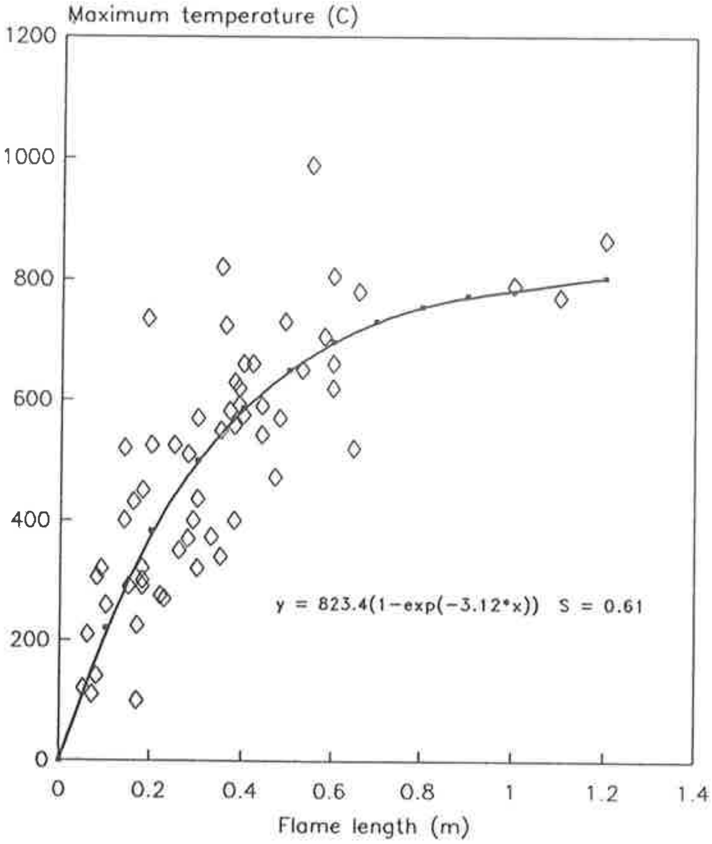


Figure 11–3: Maximum thermocouple temperature in the flames and 10 cm above the fuel bed with flame height.

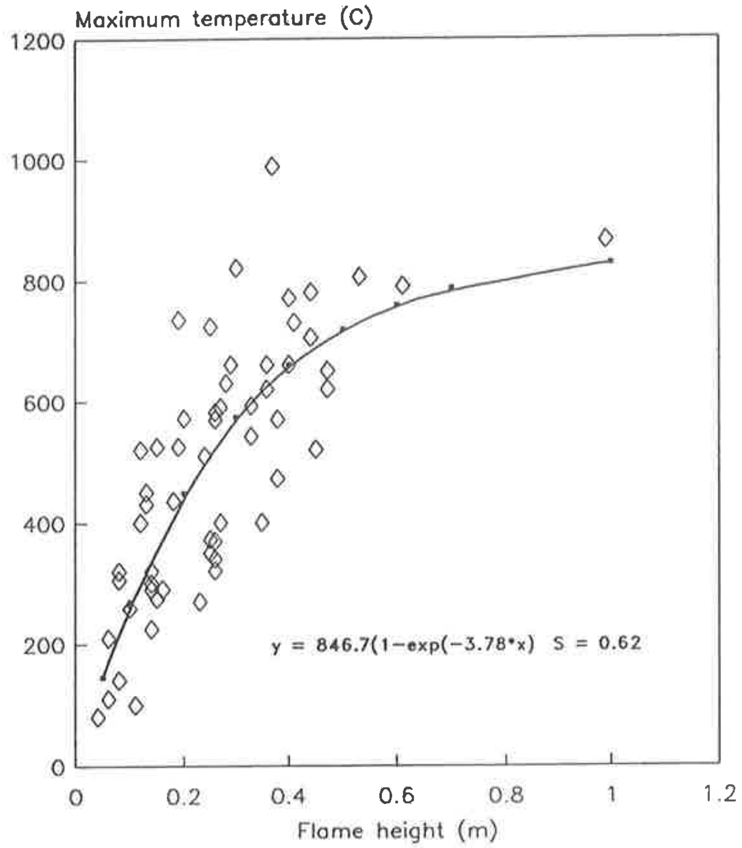
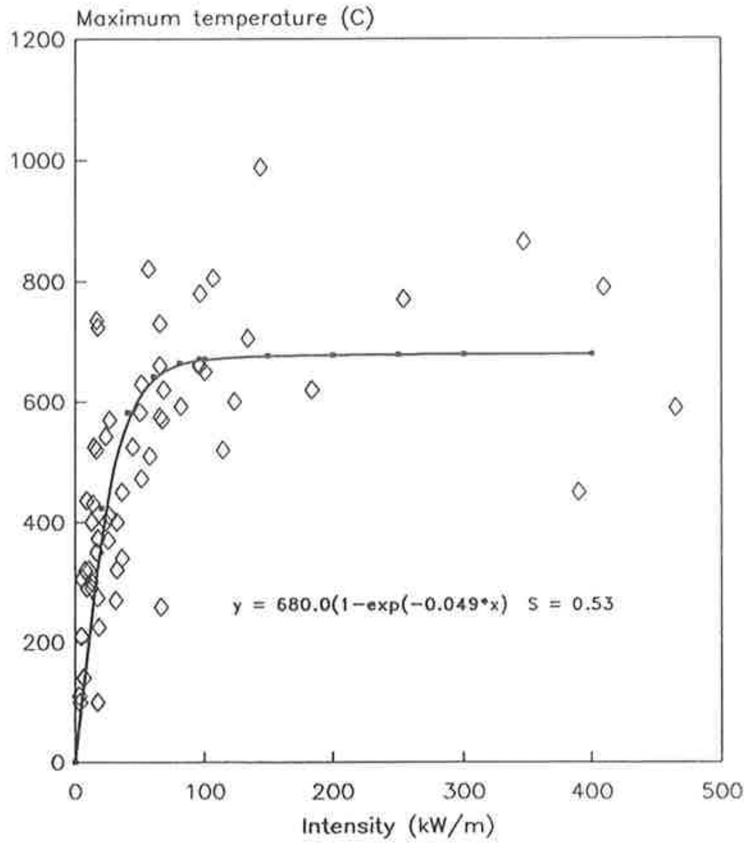


Figure 11–4: Maximum thermocouple temperature in the flames and 10 cm above the fuel bed with Byram's intensity.



The correlation coefficients in Table 11-1, and the relationships graphed in Figures 11-1, 11-2, 11-3 and 11-4 demonstrate that, in this situation, thermocouple temperature histories are meaningful expressions of the vertical distribution of heat and of the temperatures likely to be experienced by an organism at a set position in the flames. Maximum temperatures reached in the flaming zone and 10 cm above the fuel bed quickly saturates when a certain flame thickness (emmisivity) is reached; when flame length exceeds about 0.8 m and fire intensity exceeds about 100 kW m^{-1} (Figures 11-2, 11-3 and 11-4).

The height above the fuel bed at which temperature saturation is reached is likely to increase with increasing flame size and fire intensity. Thermocouples set 10 cm above the fuel bed measured temperatures at different positions of the flames relative to flame size. In some instances, 10 cm was near the base of the flame, and in other instances, 10 cm was near the tip of the flame. To examine the relationship between maximum temperature and position of the thermocouple in relation to the size of the flame, the thermocouple position was expressed as a fraction of the flame height (h_F), i.e.;

Thermocouple height ratio (h_r) = $0.1/(h_F)(m)$

Maximum temperature (T_{max}) is graphed with thermocouple height ratio (h_r) in Figure 11-5 and a regression model fitted to these data;

$T_{max} = 295.31(h_r)^{-0.635}$ Equation 11-1.

Equation 11-1 enables the maximum temperature (30 gauge wire thermocouple) at any distance above the fuel bed to be estimated, given flame height. For example, for a flame height of 0.6 m in jarrah fuels, the maximum thermocouple temperature likely at 1.3 m above the fuel can be estimated, using Equation 11-1, by;
Thermocouple height ratio = 1.3/0.6 = 2.166
Maximum thermocouple temperature (^oC) = $295.31(2.166^{-0.635})$ = 180.7^o C

This relationship is a useful guide to estimating the fire hazard to forest organisms, and provides significantly more information about the thermal environment than scorch height.

11.3.2. Heat load in the flaming zone

Heat load (H_L) (degree minutes), the mean area beneath the thermocouple temperature history trace (set 10 cm above the fuel bed), is assumed by this study to be an index of the heat pulse which would be received by an object such as a living plant stem.

H_L is strongly related to the quantity of fuel consumed (w_C) (Figure 11-6 and Equation 11-2), but is independent of rate of spread (r) (Figure 11-7) and flame depth (D). Stronach and McNaugton (1989) also reported a good linear relationship between area beneath the temperature trace and the quantity of fuel consumed for grass fires. H_L is weakly related to flame height, (h_F), flame length (L), flame depth, flame residence time (t_R) and intensity (I), probably because these variables are affected by the quantity of fuel burnt.

Heat load, used as an index and measured at a standard position and in relation to a specific fuel type, is a better measure of acute impact on vegetation near ground level, such as stem girdling and injury, than Byram's fire intensity. Fire intensity is calculated from rate of spread (which is unrelated to the heat load near the ground) and the quantity of fuel burnt in the active flaming zone, which is extremely difficult to determine in the field. In deep eucalypt litter beds, a significant proportion of the total fuel is consumed behind the active flaming zone. Heat load, calibrated for fuel type, is a measure which integrates the temperature history due to all phases of combustion, so the only measure required to calculate heat load near ground level for a given fuel complex is the total quantity of surface fuel consumed. Although heat load is directly related to the quantity of fuel consumed, it is a more meaningful measure of acute impact than the quantity of fuel consumed because it actually represents the temperature history which gives rise to the impact.

As discussed above, temperature history is a very useful measure of the severity of fire on vegetation (Stinson and Wright 1969, Wright 1970, Potter *et al.* 1983, Hobbs and Gimingham 1984 and Engle *et al.* 1989). Heat load is a reflection of temperature history and an ability to reliably predict heat load from fuel quantity consumed overcomes many of the practical problems described by Engel *et al.* (1989) of measuring it directly in the field. The predictive equations described here should apply to the field situation, as the experimental fuels were similar in structure to standard jarrah fuel (SJF) in the field.

The equation for the regression line through the origin relating heat load (at 10 cm above the fuel bed) and the quantity of fuel consumed (Figure 11-6)), is;

$H_L = 196.73(w_C)$ Equation 11-2.

Figure 11–5: Maximum thermocouple temperature as a function of height ratio (height above fuel/flame height). For example, temperature at 2 x flame height is about 200 (°C)

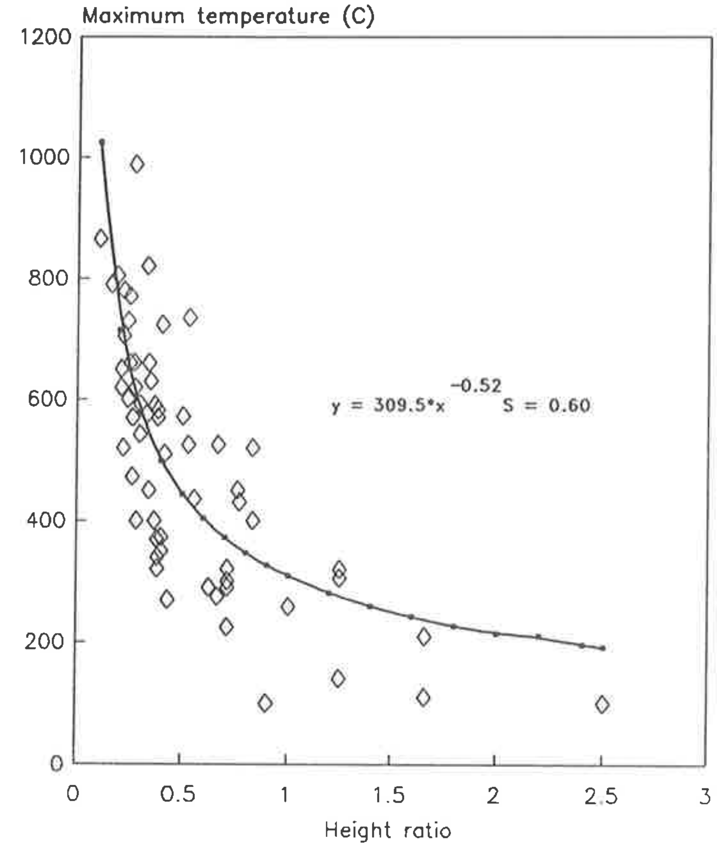


Figure 11–6: Area beneath the thermocouple temperature trace (heat load) in the flames with the quantity of fuel burnt.

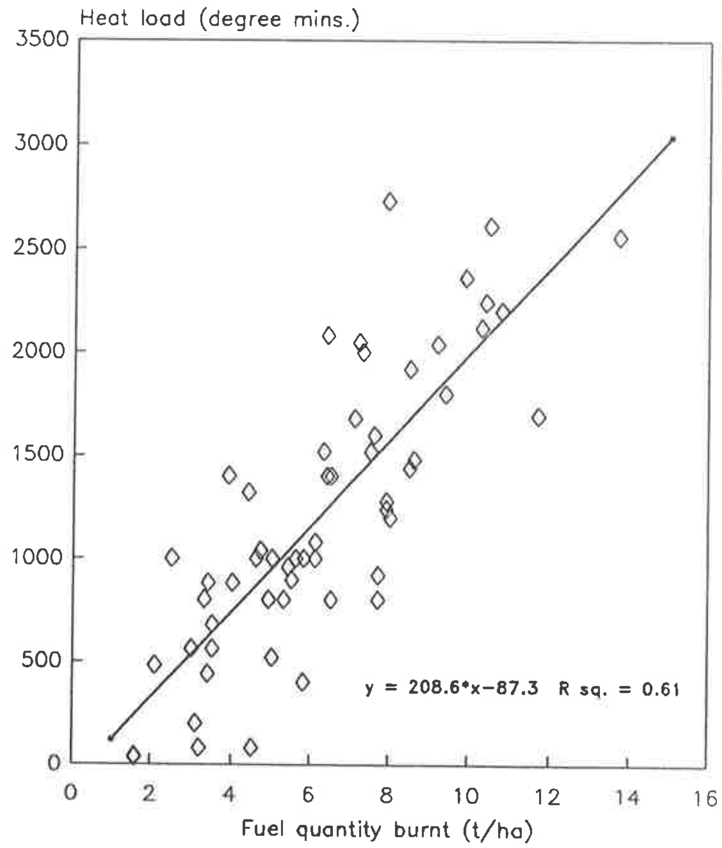
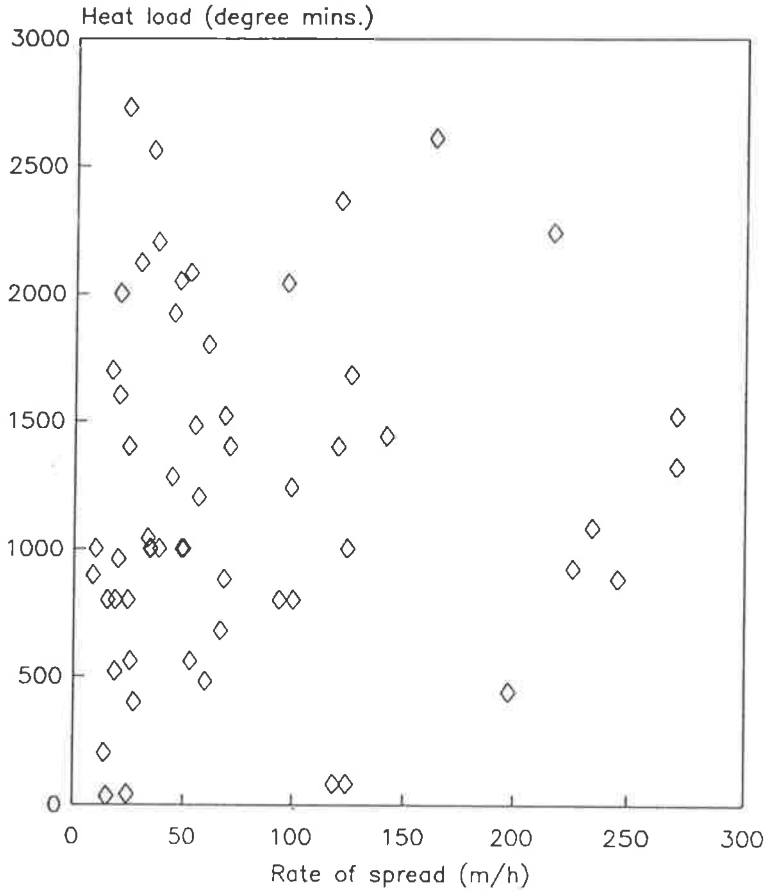


Figure 11-7: The area beneath the time/temperature trace (heat load) for a thermocouple in the flames is independent of rate of spread.



11.3.3 Heat loads and maximum temperatures measured on the bark surface and at the cambium of bull banksia stem sections.

The range of fuel and fire behaviour conditions experienced during the 38 experimental fires are summarised in Table 11-2. An example of the rapid rise and fall of temperature at the bark surface, and the delayed, gradual rise and fall of temperature at the cambial layer is graphed in Figure 11-8. Temperature at the cambium returned to ambient temperature 10-20 minutes after the passage of the flames.

Table 11-2: **Summary of conditions during experimental laboratory fires set to examine temperature histories at two locations on *Banksia grandis* stem sections.**

Variable	Minimum	Maximum	Mean
Air temperature (T_A) (°C)	18	33	25.3
Relative humidity (RH) (%)	28	84	49.7
Fuel moisture content (MC) (%)	7.0	13.0	9.8
Fuel burnt (w_C) (t ha^{-1})	3.11	14.11	6.74
Rate of spread (h_r) (m h^{-1})	11	163	80.9
Flame height (h_F) (m)	0.12	1.00	0.57
Flame length (L) (m)	0.12	1.30	0.76
Intensity (I) (kW m^{-1})	18	870	288
Stem section diameter (cm)	2.0	10.9	5.7
Stem section bark thickness (mm)	1.0	14.0	8.7
Max. temperature, bark (T_B) (°C)	211	710	422
Max. temperature, cambium (T_C) (°C)	21	99	46
Heat load bark (H_L) (degree mins)	326	1716	735
Heat load cambium (H_L) (degree mins.)	18	643	93

Figure 11–8: Example of thermocouple temperature histories on the bark surface and at the cambium on the windward side of banksia stems during experimental fires.

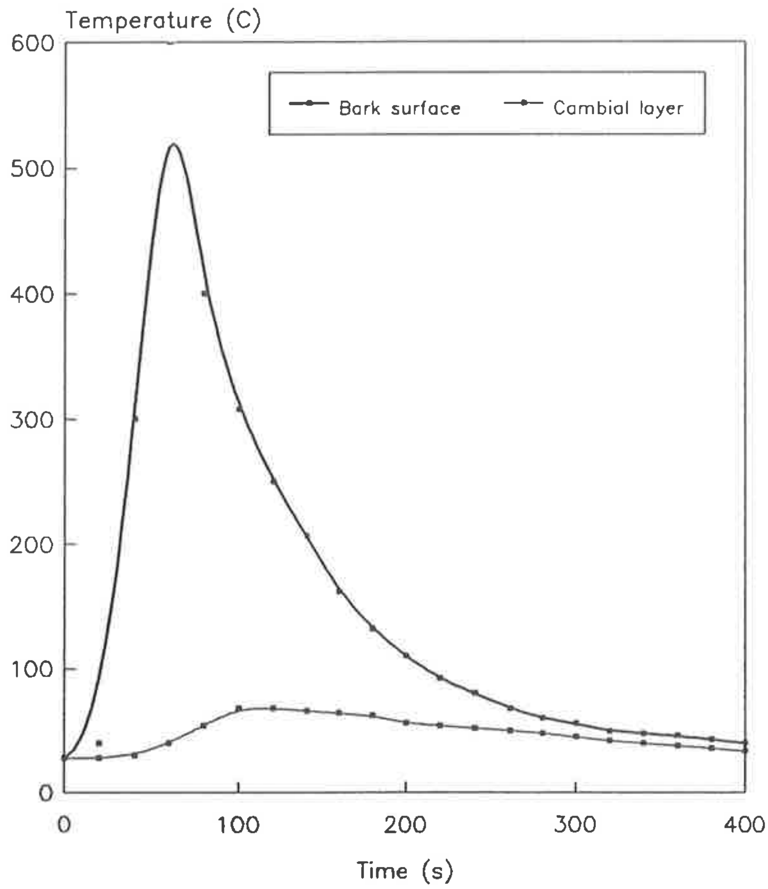


Table 11-3: Matrix of Pearson correlation coefficients. Response time (seconds) is the time difference between maximum temperature at the surface of the bark and maximum temperature at the cambium. (see Table 11-2 or Appendix 2 for description of other symbols).

Variable (s)	T_B	T_C	H_L(cambium)	H_L(bark)	Response time
w_C	0.42	0.19	0.38	0.88	-0.18
r	0.38	0.08	-0.14	0.20	-0.48
h_F	0.59	0.29	0.21	0.67	-0.07
L	0.58	0.20	0.09	0.55	-0.26
t_R	0.16	0.14	0.12	0.01	-0.24
I	0.55	0.07	0.01	0.68	-0.22
Stem diam.	-	-0.52	-0.39	-	0.52
Bark thick.	-	-0.58	-0.46	-	0.62

A Pearson correlation coefficient matrix of measures of heating and variables affecting heating is presented in Table 11-3. Heat load at both locations on the stem is strongly correlated with the quantity of fuel consumed (w_C) and bark thickness (or stem diameter). Maximum temperature reached at the bark surface correlates best with flame size and fire intensity. The rate of heat transfer through the bark (thermal diffusivity (Spalt and Reifsnyder 1962)) represented by the time difference between maximum temperature on the bark surface and maximum temperature at the cambium (response time) correlates well with bark thickness.

Multiple linear regression (least squares method) models of variables influencing the response of heat load and maximum temperature at the cambial layer were constructed using the stepwise procedure (SAS Institute 1985). Regressor variables influencing heat load (H_L) received at the cambial layer (Equation 11-3) were firstly, total quantity of fuel consumed (w_C) during all phases of combustion, and secondly, bark thickness. As with most tree species, there is a strong linear relationship between bark thickness (BT) and diameter over bark (DOB) of banksia stems (BT(mm) = 1.40DOB(cm) + 0.6 $R^2 = 0.85$), so these variables are interchangeable in regression analysis (see Equation 11-4). Interestingly, using stem diameter rather than bark thickness to predict H_L improved the regression correlation coefficient slightly, indicating that stem diameter in itself may exert an influence on heat load at the cambium.

H_L(cambium) = 21.7(w_C) - 17.85(BT) + 104.3 $R^2 = 0.47$ (Equation 11-3),
H_L(cambium) = 25.58(w_C) - 31.31(DOB) + 102.9 $R^2 = 0.51$ (Equation 11-4),
(No intercepts model: H_L = 31.9(w_C) - 22.26(DOB)).
Equation 11-3 is graphed with data points in Figure 11-9.

Figure 11-9: Heat load at the cambium near ground level and on the windward side of banksia stems graphed with fuel quantity burnt (w) by bark thickness classes (b).

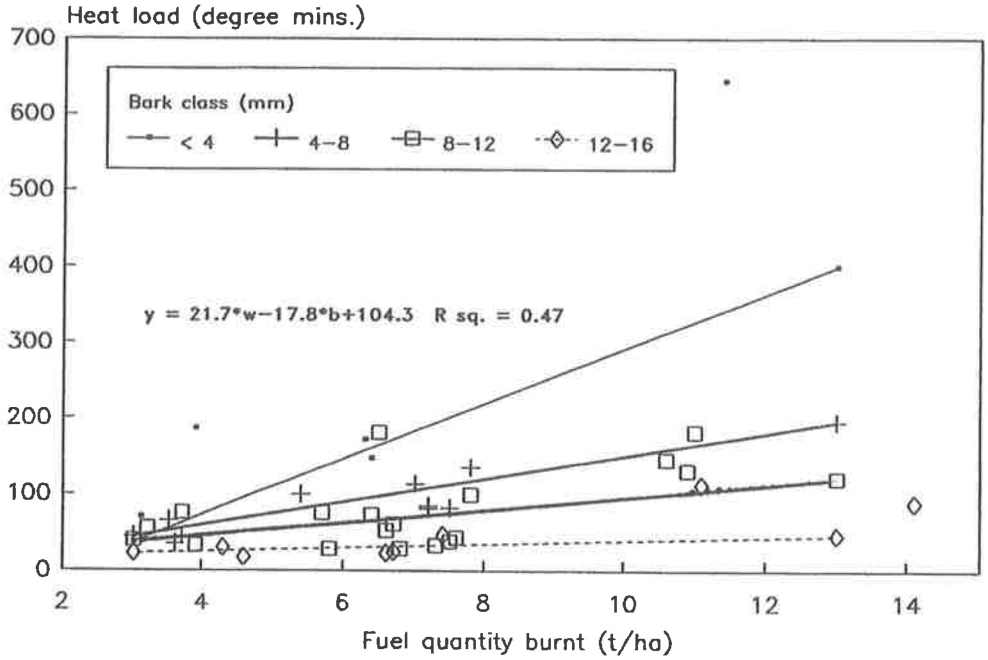


Figure 11-10: Maximum temperature at the cambium near ground level and on the windward side of banksia stems with fuel quantity burnt (w) and by stem diameter classes (d).

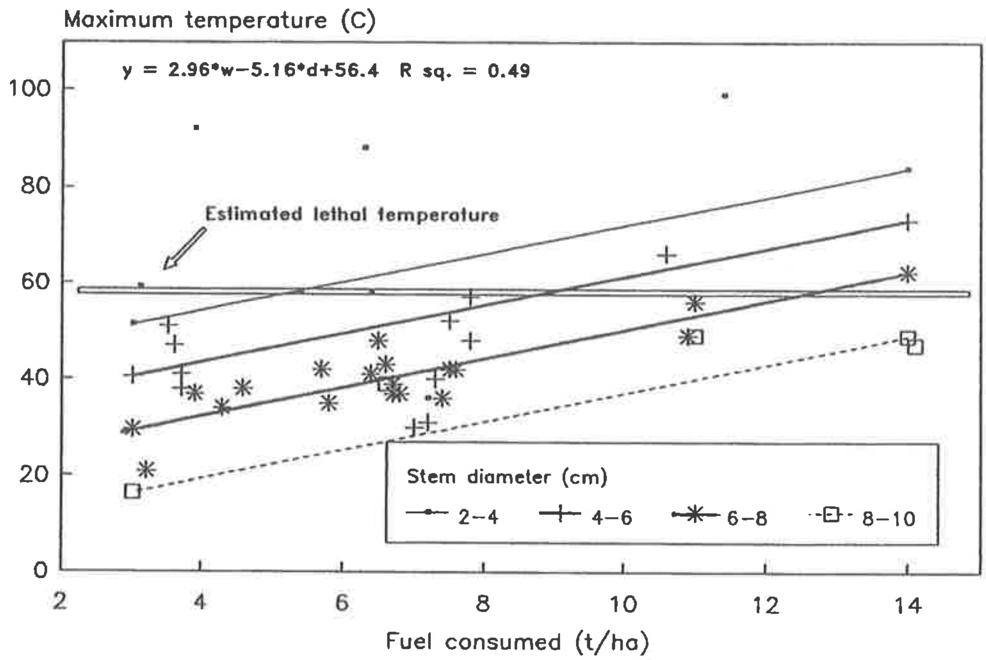
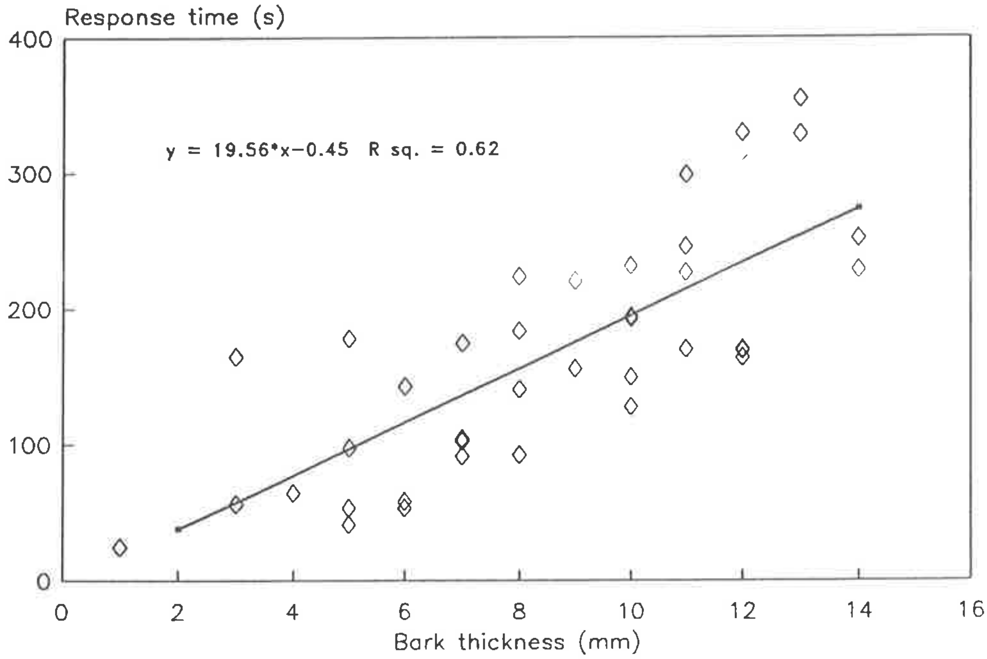


Figure 11-11: Time taken for temperature at the cambium to peak (response time) with bark thickness.



Most variation in maximum temperature reached at the cambium (T_C) near ground level and on the windward side of banksia stems is explained by bark thickness (BT (mm)) (34%) and the quantity of fuel burnt (W_C (t/ha)) (15%) (Equation 11-5 and Figure 11-10). Stem diameter (DOB (CM)) is substituted for bark thickness in Equation 11-6 and used with fuel quantity consumed to predict the maximum temperature at the cambium.

$T_C = 2.96(W_C) - 5.16(DOB) + 56.4$ $R^2 = 0.49$ (Equation 11-5),

$T_C = 2.35(W_C) - 3.05(BT) + 57.3$ $R^2 = 0.50$ (Equation 11-6).

Heat load (H_L) at the surface of the bark is strongly related to the quantity of fuel consumed. No other variables met the 0.15 significance level for entry into the model (Equation 11-7).

$H_L(bark) = 124.2(w_C) - 105.12$ $R^2 = 0.78$ (Equation 11-7).

11.4 Discussion

This study has identified fuel and fire behaviour characteristics which are meaningful measures of the impact of fire in the flaming zone. The key findings to emerge can be summarised as:

1. Maximum temperatures in the flames and at the bark surface are directly related to flame size, fire intensity and rate of spread;
2. Heat load in the flames and at the bark surface is strongly related to the quantity of fuel burnt, weakly related to flame size and fire intensity and independent of rate of spread;
3. Both maximum temperature and heat load at the cambium are related to bark thickness (or stem diameter) and the quantity of fuel consumed and are independent of fire intensity and rate of spread;
4. The response time, the time taken for the cambium to reach maximum temperature, is a function of bark thickness.

11.4.1 Defoliation height

Flame temperature is not a measure of heat energy output but is likely to reflect the impact of fire on exposed living plant tissue such as leaves and the fine stems of small understorey plants with very thin live bark. Thermal death time decreases exponentially with increasing temperature (Hare 1961 and others), so unprotected tissue exposed for short periods to the high flame temperatures will be killed.

In most instances, low, multi-stemmed jarrah forest understorey shrubs are killed (to ground level) by even the mildest fire and fine live material less than about 4 mm in diameter is consumed in the flaming zone (see Chapter 7). Defoliation height, the height to which vegetation is consumed, is at least equal to the height of the flames.

11.4.2 Stem damage and mortality

In these laboratory experiments, maximum temperature and heat load at the cambium near ground level on the windward side of banksia stems was independent of flame temperature, fire intensity and rate of spread. This observation is not consistent with observations of stem damage in the jarrah forest. Burrows (1985) found that the probability of a banksia stem being killed by fire was a linear function of stem size (or bark thickness) and fire intensity. That is, controlling for bark thickness and the quantity of fuel consumed, mortality increased with increasing heat flux, as characterised by fire intensity.

Plate 11-2: Bull banksia trees killed by intense fire (4,500 kWm^{-1})

Plate 11-3: Stem epicormic shoots on jarrah and marri trees following a severe fire which defoliated the trees

Similarly, Nicholls (1974) found that bole damage to pole size (15-30 cm diameter at breast height) jarrah trees in the field was dependent on fire intensity. Although no fuel quantity details are given by Nicholls, the intensity treatments were randomly allocated to adjacent plots of relatively uniform forest structure and of the same fuel age. Average flame heights were 0.6 m and 8.7 m in the low and high intensity treatments respectively. Vines (1968) recorded low temperature increases at the cambium (leeward side) of several eucalypt species, including jarrah, during low intensity prescribed fires (<250 kW m^{-1}), but significant rises in cambial temperature following "fierce fires".

Burrows (1987a) studied factors predisposing jarrah and marri trees to fire damage in the field and concluded that the likelihood of a tree sustaining stem damage was dependent on a number of factors including stem diameter, bark thickness, tree species, growth habit, proximity of coarse fuels such as logs, extent of previous damage and fire intensity. A clearly defined relationship between fire intensity and bole damage could not be developed from the data, but the incidence and severity of bole damage was significantly higher in the moderate intensity class (600-1,500 kW m^{-1}) than in the low intensity class (<600 kW m^{-1}) when other predisposing factors were controlled.

Laboratory and field results appear contradictory, but both can be explained. Fire-caused stem damage can be categorised as;

i) complete girdling of the stem at or near ground level resulting in stem death,
ii) partial death of the cambium on the tree bole giving rise to a fire-scar.

Field observations and the data presented above suggest that each condition is caused by a separate process. The following discussion is in relation to fire-caused stem damage associated with the combustion of fuels in the flaming zone and excludes the other contributing factors mentioned above such as tree habit, previous injuries and proximity to coarse fuels such as logs.

During these laboratory experiments, cambial temperature was measured near ground level and on the windward side of relatively small diameter stem sections and was found to be independent of fire rate of spread and fire intensity. This finding is consistent with field temperature measurements e.g., Fahnestock and Hare (1964) reported that temperatures on the windward side of tree boles during fast spreading headfires were similar to those during slow spreading backfires. During a forest fire, the windward side of a stem is the coolest sector on the cambial circumference, with highest temperatures being recorded on the leeward side (Fahnestock and Hare 1961, Aston and Gill 1968, Gill 1974 and Costa *et al.* 1991). Fire behaviour on the windward side is relatively stable. By contrast, the leeward side of a stem is subjected to turbulent airflow resulting in intense heating and localised erratic fire behaviour characterised by a concentration of intense flaming activity for some distance higher up the stem than the actual surface fire (chimney effect). Gill (1974) studied this phenomenon in the laboratory using a gas flame and steel cylinders and found that the chimney effect intensified with increasing fuel supply, flame size and wind speed. Tunstall *et al.* (1976) measured temperatures between strips of asbestos wrapped around cylinders placed in grass fires and found that most variation in maximum temperature on the leeward side was explained by a linear function of rate of spread and flame height. They also reported that highest temperatures on the leeward side were recorded about 40 cm above ground, which is also the region in which most fire-scars were observed in jarrah trees following intense fires (Burrows 1987a). Thus, the chimney effect is an important cause of fire scars (partial death of the cambium) (Gill 1974) on tree boles. Factors which determine the severity of the chimney effect; fuel supply, flame size

Plate 11-4: The "chimney" effect. Intense heating on the leeward side of the bole caused by flame turbulence.

Plate 11-5: Fire scar on the bole of a marri tree caused by the "chimney effect".

Plate 11-6: Large jarrah trees with thick protective bark are rarely damaged, even by high intensity fires.

Plate 11-7: The boles of small trees can be damaged during low intensity fires under dry conditions as the bark readily ignites on the tree.

and wind speed, are correlated with fire intensity. Many eucalypt trees, as well as behaving like cylinders in terms of aerodynamics and the chimney effect, are also potential fuel rods in a fuel bed. During a fire, bark burns on the tree and under dry conditions bark thickness can be reduced by up to 30% during intense fires (Gill *et al.* 1986a and Burrows 1987a). Bark combustion and reduction is greatest on the leeward side, which, coupled with intense fire behaviour associated with the chimney effect, increases the likelihood of cambial death.

Stem mortality (as opposed to stem injury) will depend on whether the cambium on the windward side (the "coolest" side) of the tree experiences a lethal temperature regime; which is a function of bark thickness (or stem diameter) and the quantity of fuel burnt (Equations 11-5 and 11-6). However this does not entirely explain the relationship between fire intensity and mortality rate in populations of *Banksia grandis* in the field (Burrows 1985). Fire intensity is calculated from the quantity of fuel consumed which probably explains part of its association with stem mortality. Fire intensity does relate to the intensity of the chimney effect and to the temperatures experienced on the leeward side of a tree (e.g. see Fahnstock and Hare 1964 and Tunstall *et al.* 1976). For small stemmed trees such as *Banksia grandis*, it is likely that, according to the second law of thermodynamics, heat on the leeward side is conducted around the stem, resulting in higher temperatures on the windward side. There is some supporting evidence for this from field experiments. Tunstall *et al.* (1976) found that the temperature difference at 40 cm above ground between the leeward and windward side of cylinders during grass fires was very small for small diameter cylinders (7 cm), but was about 100 $^{\circ}$C for large diameter cylinders (34 cm). This, together with the role of fuel quantity, may explain the relationship between fire intensity and mortality rate in *Banksia grandis* populations reported by Burrows (1985). In addition, high intensity fires usually result in full scorch or defoliation of the canopy (Chapter 10). Loss of foliage may impede cooling processes within the stem associated with fluid movement in the phloem and possibly the xylem.

Fire injury leading to fire-scarring, or partial death of the cambium, depends on bark thickness (stem diameter), flame height, wind speed, rate of spread and the quantity of fuel consumed. These factors are well integrated by Byram's fire intensity, which probably explains the observed correlations between fire intensity and stem damage described above. Therefore, the quantity of fuel consumed is the single most important fire related factor affecting both stem death and stem damage.

For management application, stem size and the quantity of fuel burnt or stem size and fire intensity can both be used to estimate stem mortality for small stems. The relationship between bark thickness and stem diameter is similar for both bull banksia stems and jarrah stems

(Burrows 1985, 1987a) so Equations 11-5 and 11-6 can be used to estimate stem mortality for both species. This assumes that thickness is the most important factor affecting the bark thermal properties; bark structure, composition, density and moisture content have minor influences on thermal properties (Spalt and Reifsnyder 1962, Hare 1963, Reifsnyder *et al.* 1967, De Ronde 1982). Both Vines (1968) and Gill and Ashton (1968) have shown that, although bark type in eucalypts does affect their tolerance to fire, bark thickness is by far the most important characteristic.

Predictions of the largest stems (banksia and jarrah) likely to be killed by fire for a given fuel consumption are graphed in Figure 11-12. Burrows (1985) derived a field based model for predicting the probability of a *Banksia grandis* stem being killed by fire from stem size and fire intensity (Figure 11-13).

Reliably estimating fire injury, or fire-scaring to tree boles is extremely difficult because of the large number of variables involved (Burrows 1987a). Excluding factors such as previous fire injury and proximity to logs, fire behaviour on the leeward side of a stem where most fire-scaring occurs, will vary according to very localised fuel conditions and wind flow.

Burrows (1987b) found that even low and moderate intensity fires under warm dry summer conditions (Soil Dryness Index > 1200) caused significant bole injury to jarrah and marri trees when trees were near (< 2 m) burning coarse woody material such as logs and limbs. Trees most likely to be injured during summer fires were small trees (< 20 cm dbhob), trees with old, exposed injuries which had not fully occluded (dry sides), trees near logs (<2 m) and trees which had resprouted from stumps (coppice stems). Most healthy trees larger than about 20 cm dbhob and which were further than 2 m from coarse fuels were able to tolerate fire intensities at least up to 1,500 kW m^{-1} without injury.

Raw data gathered by Burrows (1987a) were re-analysed here. Due to the highly variable nature of the data, stem damage could not be reliably modelled from discrete measures of fire intensity and stem diameter. However, the probability of a jarrah stem being damaged by fire for broad stem diameter and fire intensity classes was determined from the number of trees damaged as a fraction of the total number of trees in each diameter/intensity class. A weak but significant linear regression through the origin was fitted to the data and the predicted probabilities are shown in Table 11-6. These probabilities apply to single stemmed jarrah trees which had not experienced fire for at least 7 years, which had no stem or bark damage prior to experimental fire and which were more than 2 m from the nearest piece of coarse fuel (logs and limbs). Cambial damage caused by the chimney effect occurred on the leeward side of stems from just above ground level to a height of about 2 m.

Figure 11-12: Predicted maximum stem diameter likely to be killed by fire vs the total quantity of fuel consumed. Banksia grandis and jarrah stems of similar diameter have similar bark thickness, so similar fire resistance.

Figure 11-13: Probability of a banksia or jarrah stem being killed by fire vs fire intensity for a range of stem sizes. (Source: Burrows 1985)

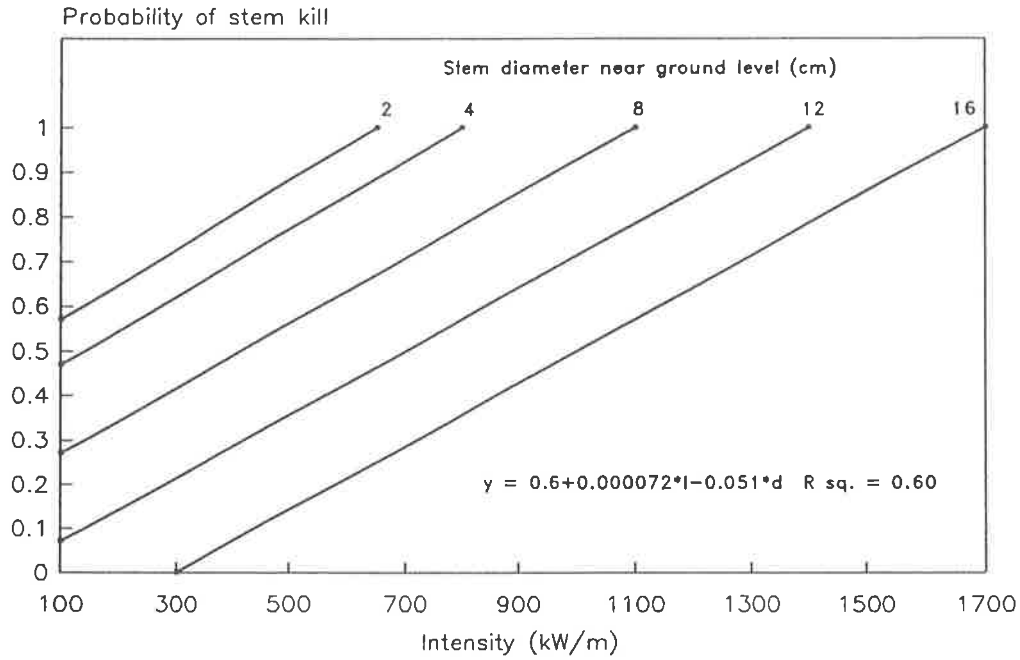


Table 11-6: Predicted probability of a jarrah tree incurring some form of cambial damage on the leeward side of the bole as a result of flaming combustion during fires in summer or autumn when the Soil Dryness Index (Mount 1972 and Burrows 1987b) is > 1200 (n = 155).

	Fire intensity class (kW m^{-1})				
Stem dbhoh class (cm)	<500	500-1000	1000-1500	1500-2000	2000-3000
5-10	0.12	0.37	0.62	0.86	1.0
10-20	0.05	0.16	0.27	0.38	0.55
>20	0.03	0.07	0.12	0.17	0.25

11.5 Concluding discussion

Thermocouples used in the flames and beneath the bark of bull banksia stem sections in the laboratory proved to be a meaningful technique for linking fuel and fire behaviour factors to temperature histories. Flame temperatures, at fixed locations in relation to the fuel bed, relate well to commonly used measures of fire behaviour such as flame size, rate of spread and fire intensity. However heat load (the area beneath the temperature history trace) and maximum temperature at the cambium depended on bark thickness and the quantity of fuel burnt and was independent of fire behaviour. Bark thickness also had an important affect on the response time, or the time taken for the cambium to reach maximum temperature.

Relationships developed from this study and from field studies by Burrows (1985 and 1987a) can be used to estimate bull banksia and jarrah stem mortality from fuel consumed and fire intensity. Stem injury is more difficult to predict because it is usually associated with intense fire behaviour on the leeward side of the stem. However, some estimates of the probability of stem injury can be made for stem diameter classes and fire intensity classes.

CHAPTER 12

FIRE IMPACT BENEATH THE FLAMES: SOIL HEATING

12.1 Introduction

Soil heating during forest fires can have many pronounced effects on soil physical and chemical properties and on the biological responses of soil flora and fauna (e.g. Wells 1971, Wells *et al.* 1979, Warcup 1981, Flinn *et al.* 1983, Clinnick 1984, Groves *et al.* 1986, and Walker *et al.* 1986). Of the total energy radiated from a forest fire, only about 5-8% is transferred to the soil (Packham 1970 and Debano 1974). Factors which affect soil heating during a fire are reasonably well understood in general terms and include the quantity of fuel burnt, soil moisture and soil thermal properties (Scotter 1970, Hanks *et al.* 1971, Wells *et al.* 1979 and Hungerford 1989). In moist soils the transfer of heat is more complicated because temperature gradients cause movement of moisture and vapour and transport of sensible and latent heat (De Vries 1963 and Ashton and Gill 1976).

A number of jarrah forest understorey species, particularly species of the legume families, depend on soil stored seed for regeneration following the death of the parent plant (Christensen and Kimber 1975, Shea *et al.* 1979, Bell and Koch 1980 and Bell *et al.* 1993). Heat induces the seeds of these species to germinate (Shea *et al.* 1979 and Bell *et al.* 1993), a trait common to a number of species in other vegetation types in fire prone environments (e.g., see Cunningham and Cremer 1965, Floyd 1966, 1976, Martin and Cushwa 1966, Martin *et al.* 1975, Fox and Kanagas 1985, and Portlock *et al.* 1990). In jarrah forests, the development of dense legume thickets is often associated with intense summer wildfires (Peet and Van Didden 1973).

Plate 12-1: Dense legume regeneration from soil stored seed following a summer fire under dry fuel and soil conditions.

Regeneration of legume thickets following fire is of considerable interest to jarrah forest managers and is discussed in some detail in Chapters 1 and 3. Briefly, research evidence suggests that promoting legume species in the understorey could significantly reduce the susceptibility of the forest to the soil-borne fungal pathogen *Phytophthora cinnamomi* (Shea 1975, Shea *et al.* 1976, Shea and Malajczuk 1977 and Shea *et al.* 1979). Legume thickets are also important for a number of animal species, providing food and shelter (Christensen 1977, Christensen *et al.* 1981)

To promote legume thickets, fire ecologists have advocated for fires of a higher intensity and set at a drier time of year than fires which are normally prescribed for fuel reduction. Shea *et al.* (1979) and Christensen and Kimber (1975) observed that the best germination occurred when fuels were plentiful and dry, when soils were dry, and fires were intense. Shea *et al.* (1981) suggest that fire intensities of 800-1,200 kW m^{-1} are required for good thicket regeneration. These recommendations, and observations of dense legume regeneration following intense wildfires, has led fire managers and researchers alike characterizing fires needed to produce this response as "hot fires" or "intense fires" (e.g. see Auld 1990). However, limited research indicates that fire intensity *per se* and rate of spread do not influence soil heating (see review by Hungerford 1989), so a more meaningful characterisation of fire in terms of its impact on the soil is needed.

There have been a few attempts to develop physical or numerical models of soil heating based on principles of heat transfer. Scotter (1970) developed a simple model to describe soil temperatures during grass fires, but did not include the effects of soil moisture. Aston and Gill (1976) proposed a numerical model which coupled the transfer of heat, water, and vapour in the soil. Their model was tested under laboratory conditions using an artificial heat source and found to work reasonably well. Pafford *et al.* (1985) proposed a theoretical model linking flame residence time, flame temperature and flame geometry with soil heating. Steward *et al.* (1989) presented a method for predicting the lethal heat penetration in soil beneath a spreading fire but the analytical model requires detailed information about the physical properties of the soil, the duration of heating by fire, and the Newtonian cooling coefficient at the soil surface. Dimitrakopoulos and Martin (1990) proposed a mathematical model based on a constant temperature or a constant heat pulse applied to the soil surface. The models described above have been validated in the laboratory using artificial heating devices but have not been tested in the field where vegetation fuel is the heat source.

Attempts at modelling soil heating from first principles, or developing models in the laboratory using artificial heat sources, provide an understanding of the soil thermodynamics but are limited in there application. Hungerford *et al.* (1991) suggest that none of the models have the ability to link pre-fire conditions, fire characteristics and soil heating. As noted by Hungerford (1989), such models deal with only part of the system; they have not dealt with bushfire as the heat source. Recognising this shortcoming, Hungerford (1989) proposed a concept which identified bushfire as the heat source, soil as the heat transfer medium and soil-borne plant organs as the recipient of heat.

In managing ecological systems such as the jarrah forest, it is important to understand the relationship between heat pulse received by the soil, environmental and behavioural characteristics of fire, and soil organism responses so that prescribed fires can be applied which produce the desired result. There are no models, empirical or physical, which are able to quantitatively link fuel, soil and fire behaviour characteristics in relation to soil heating during jarrah forest fires.

This study aims to develop a biological index of soil heating using jarrah litter fuel as the heat source and incorporating appropriate fuel, fire and soil characteristics important in affecting heat pulse into the soil in a quantitative model.

12.2 Methods

The nature of biological responses induced by soil heating depends primarily on the soil temperature and duration of heating (Wells *et al.* 1979 and Walker *et al.* 1986), so in this study thermocouples were used to measure maximum temperatures and temperature histories experienced at various depths in the soil.

The experiments were conducted in the fire laboratory described in Chapter 7. Prior to undertaking laboratory experiments, field measurement of soil heating during jarrah forest fires was attempted in conjunction with the fire behaviour experiments described in Chapter 8. Initially, grids of thirty 16 gauge chromel-alumel thermocouples were established in the plots and at various depths in the soil. After about ten fires, the experiment was eventually abandoned due to a number of logistical and physical problems which could not be satisfactorily resolved. These included:

i) Disturbance to the fuel layer and the soil during the laying out and positioning of the thermocouples and connecting cables.

ii) The need to insulate thermocouples and connecting cables. A cold junction was necessary to prevent erroneous readings due to the thermocouple wire and connecting cable acting as a thermocouple at the join.

iii) Laying out the thermocouple grids was very time consuming and held up fire behaviour research.

iv) Falling debris during and soon after the fire, and fleeing animals (particularly kangaroos) completely upset the positioning of the thermocouples.

v) Variables such as fuel quantity, fuel moisture, fire behaviour and soil moisture could not be controlled in the field.

vi) Early results showed that soil temperatures were highly variable even within the 2 m x 2 m grid of thermocouples.

It is probably for similar reasons that there is a dearth of literature reporting soil temperatures during forest fires.

Laboratory fires were conducted on the fire table described in Chapter 7. Fresh fine litter, < 6 mm in diameter, was collected from the jarrah forest floor and used as fuel. Before each experimental fire, a known weight of fuel of known moisture content was placed on the table and arranged as described in Chapter 7. Grey sandy soil extracted from a sand pit in a jarrah forest near Manjimup was screened and spread evenly over the table to a depth of 100 mm for each fire. This soil type was used because it is commonly associated with the jarrah forest, it is relatively uniform in texture and structure, and was readily available. Although Ashton and Gill (1976) reported differences in soil heating between clay and sand, Portlock *et al*. (1990) reported no significant difference in heating between different soil types found in upland jarrah forest.

Soil moisture content was varied either by oven drying it or by mixing it with varying proportions of water in a cement mixer. Moisture content was determined before each fire by drying samples in an oven. In the field, the surface moisture content (top 30 mm) of grey sandy soils is often as low as 2-3% of odw during summer and the field capacity is at about 10-12%. After each fire, the sand was removed from the table and a fresh batch applied for the next fire.

Two banks of 16 gauge chromel-alumel thermocouples were fixed near the centre of the table and 0.5 m apart. Each bank consisted of four thermocouples fed up through the bottom of the table and set at various depths below the surface of the soil. The positioning and depth of the thermocouples was fixed at 0 mm (on the soil surface), 5 mm, 10 mm and 15 mm, by mounting them on non-flammable "hardiflex" asbestos-like boards which were fixed to the bottom of the table. The fused tips of the thermocouples (the probes) protruded about 15-20 mm from the mounting boards and the cables were insulated to prevent heat conduction from the boards to the thermocouples. Each thermocouple was off-set in the vertical plane by 20 mm so as not to impede the heat pulse received by the lower thermocouple. The temperature measuring system was calibrated prior to the study using ice and boiling water. During and after the passage of flames each probe was read every 16 seconds until the temperature had returned to within 5 ^{o}C of ambient soil temperature.

Average fire rate of spread, flame depth and flame height were recorded for each fire and the fans used in the experiments described in Chapter 7 were used to vary the rate of fire spread. The quantity of fuel burnt was determined by weighing the fuel before and the residue after each fire. Byram's (1959) fire intensity was calculated using rate of spread, the total quantity of fuel consumed and a heat yield of 18,700 kJ kg^{-1}.

Two measures of soil heating were used in the analysis:

i) Maximum temperature (^{o}C).

ii) The area beneath the temperature history trace (heat load (H_L) in degree minutes).

A mean value of each measure was obtained for each fire from the two thermocouples set at the same depth in the soil (one on each bank) and was used in analysis.

Plate 12-2: Fire-induced soil heating was examined in the laboratory using thermocouples and jarrah forest litter fuel as the heat source.

12.3 Results and discussion

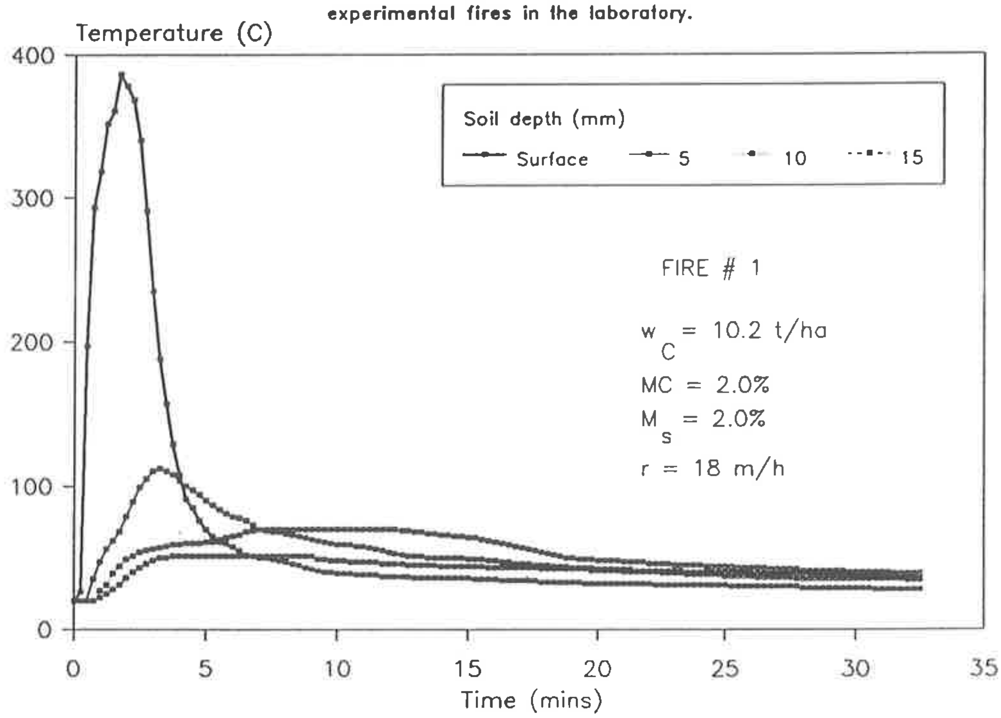
The range of variable values experienced during the 55 soil heating experiments are contained in Table 12-1.

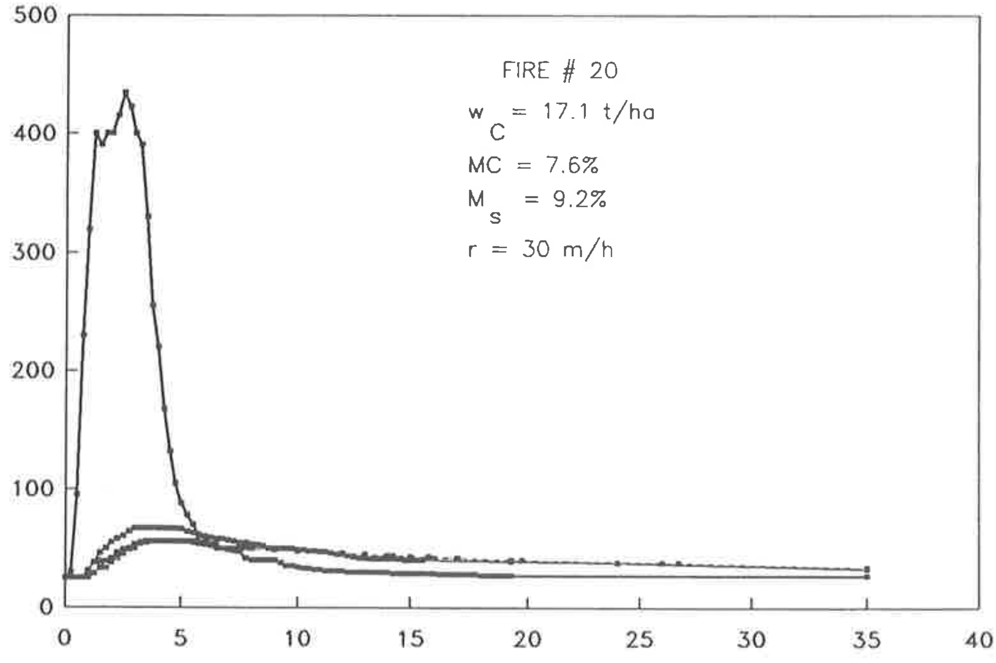
Table 12-1: Descriptive statistics showing the range of conditions during soil heating experiments in the laboratory.

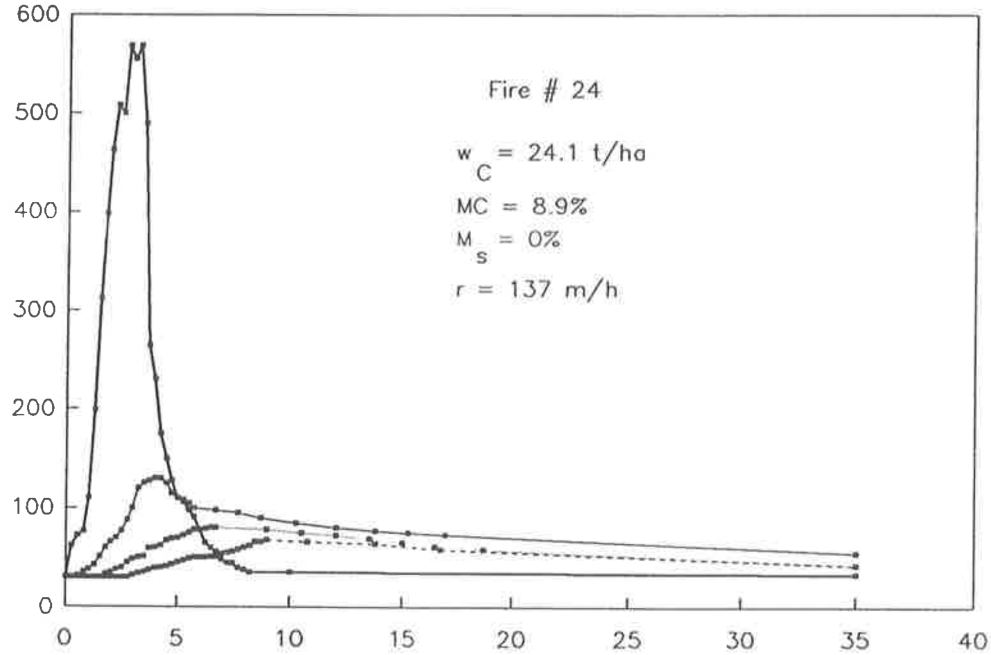
Variable	Mean	Range
Fuel consumed (w_C) (t ha^{-1})	10.3	3.1- 24.7
Fuel moisture (MC) (%)	10.4	1.9-17.4
Soil moisture (M_S) (%)	4.2	0-19.0
Rate of spread ® (m h^{-1})	26.5	8.4-123.0
Intensity (I)(kW m^{-1})	129.6	22.5-1334.0
Flame height (h_F) (cm)	32.9	10.0-140.0
Flame depth (D) (cm)	24.0	3.0-132.0
	Soil temperatures	
Ambient soil temp. (T_{AS}) (^oC)	24	18-34
Max. temp. at surface (T_0) (^oC)	371.2	278-596
Max. temp. at 5 mm (T_5) (^oC)	66.4	32-132
Max. temp. at 10 mm (T_{10}) (^oC)	49.4	27-95
Max. temp. at 15 mm (T_{15}) (^oC)	40.3	25-80
[1]Heat load at surface (H_{L0})	731.4	42-2064
[1]Heat load at 5 mm (H_{L5})	366.4	29-1512
[1]Heat load at 10 mm (H_{L10})	270.4	17-1200
[1]Heat load at 15 mm (HL_{15})	197.8	0-940
Response time (r_T) (s)	234	78-422

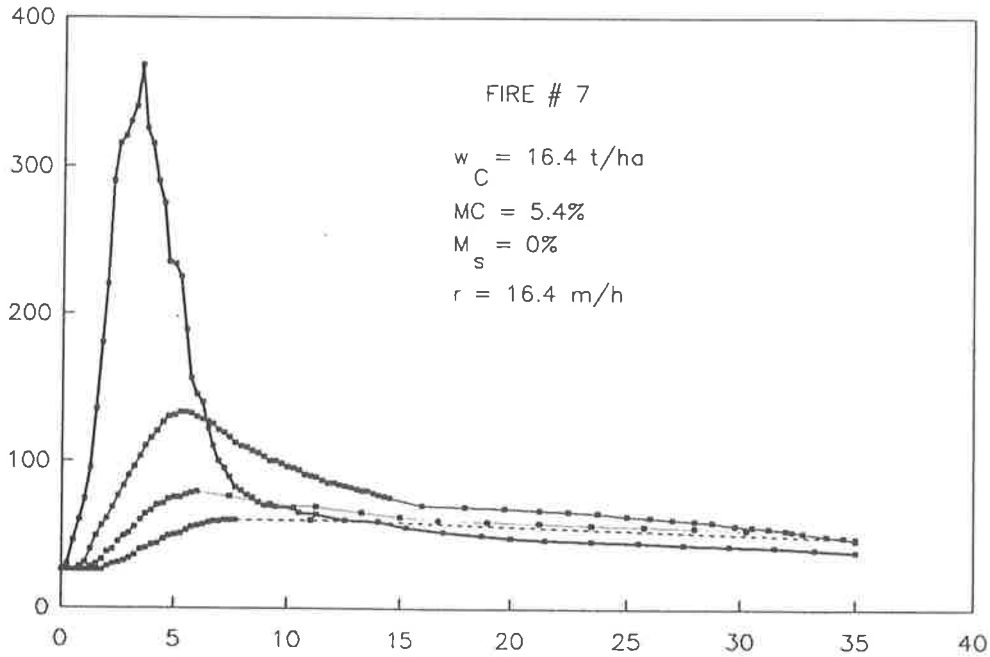
Fuel moisture content was sufficiently low (< 18% of odw) in all experimental fires to ensure complete combustion of the fuel. The insulative properties of soil are demonstrated in the temperature history traces shown in Figure 12-1. Although maximum temperatures at the soil surface were mostly between 300 ^oC and 500 ^oC, temperatures did not exceed 80 ^oC at a depth of 15 mm. The examples in Figure 12-1 also demonstrate the effects of fuel quantity, fuel moisture and soil moisture content on heat transfer to the soil. Temperature and heat load increased with fuel quantity consumed and decreased with increasing soil and fuel moisture content.

Figure 12-1: Examples of soil temperature histories on the soil surface and at depths of 5 mm, 10 mm and 15 mm during experimental fires in the laboratory.



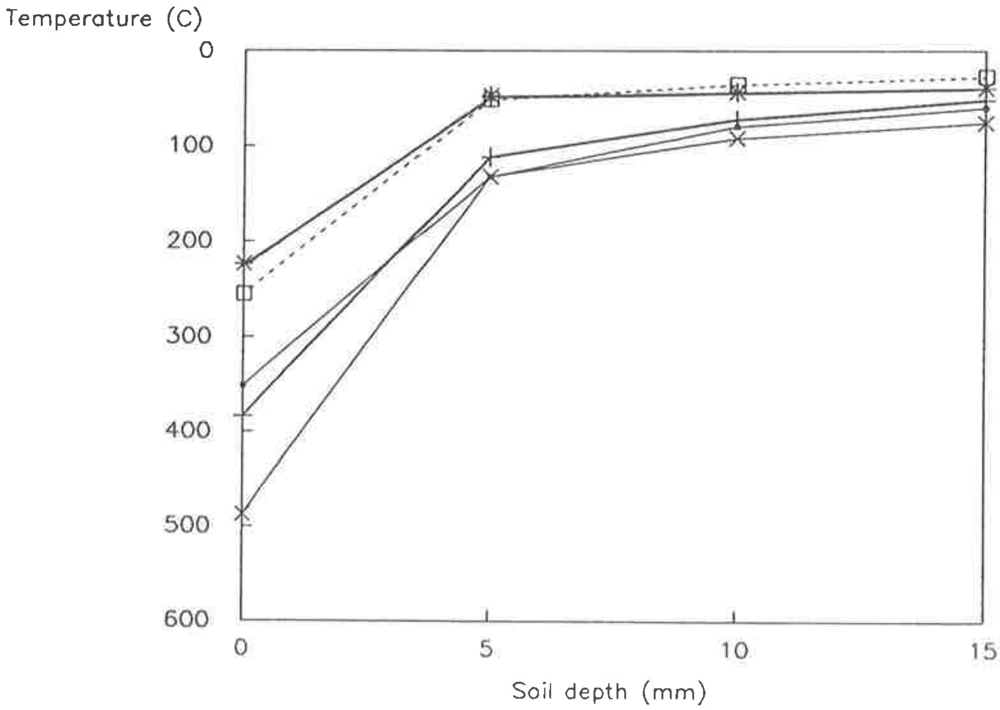



Fire # 24
w_C = 24.1 t/ha
MC = 8.9%
M_s = 0%
r = 137 m/h
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40


FIRE # 7
w_C = 16.4 t/ha
MC = 5.4%
M_s = 0%
r = 16.4 m/h
400
300
200
100
0
0
5
10
15
20
25
30
35
40

Temperature at the soil surface increased sharply with the arrival of flames (Figure 12-1) and cooled quickly after the flames had passed. The heat flux generated at the soil surface by the combustion of the litter fuel moved down through the soil on a front with up to 7 minutes elapsing before the maximum temperature was reached at a depth of 15 mm. Temperatures at the soil surface remained above 100 ^{o}C for 1-3 minutes, depending on the quantity of fuel burnt and the amount of residual ash on the soil surface. Residue tended to act as a thermal blanket, slowing the cooling process. Sub-surface soil temperatures remained above ambient for up to 70 minutes. Examples of the initial rapid decline in maximum temperature with increasing soil depth are shown in Figure 12-2. The shape of the temperature verses depth graph is similar to that reported in the literature (e.g., Scotter 1970, Ashton and Gill 1976).

Figure 12–2: Maximum temperature at various depths in the soil during laboratory fires burning in jarrah litter fuel.



Pearson correlation coefficients between measures of soil heating, soil moisture content, fuel and fire behaviour variables are shown in Table 12-2.

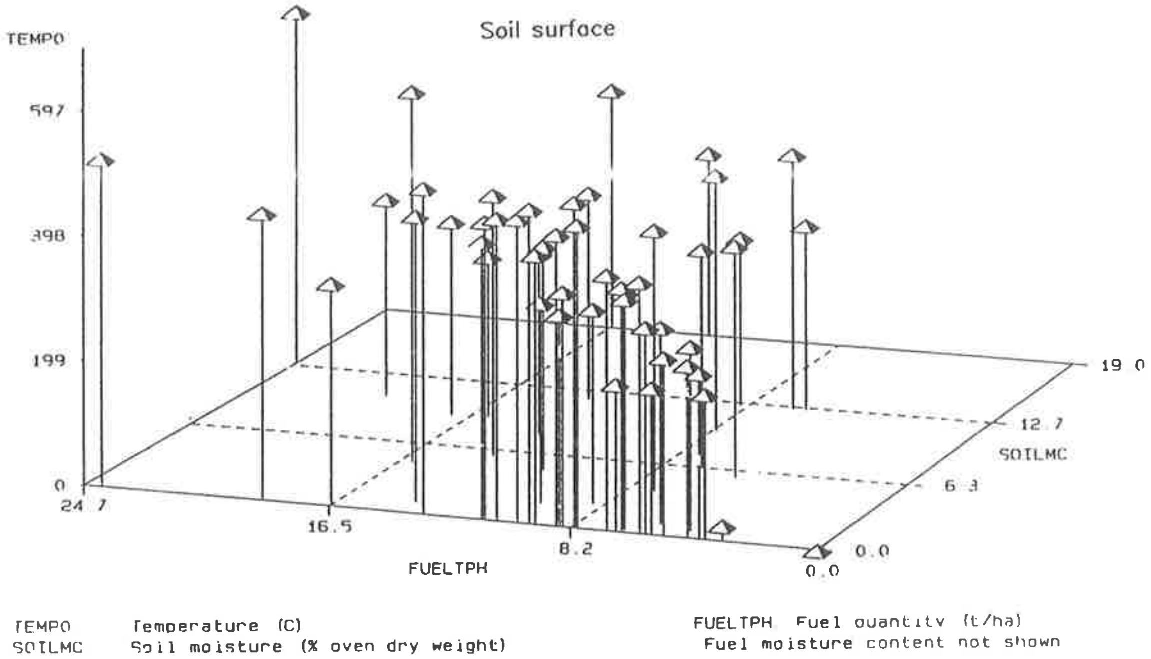
Table 12-2: Pearson correlation coefficient matrix for variables measured during soil heating experiments in the laboratory. Variable codes are as shown in Table 12-1.

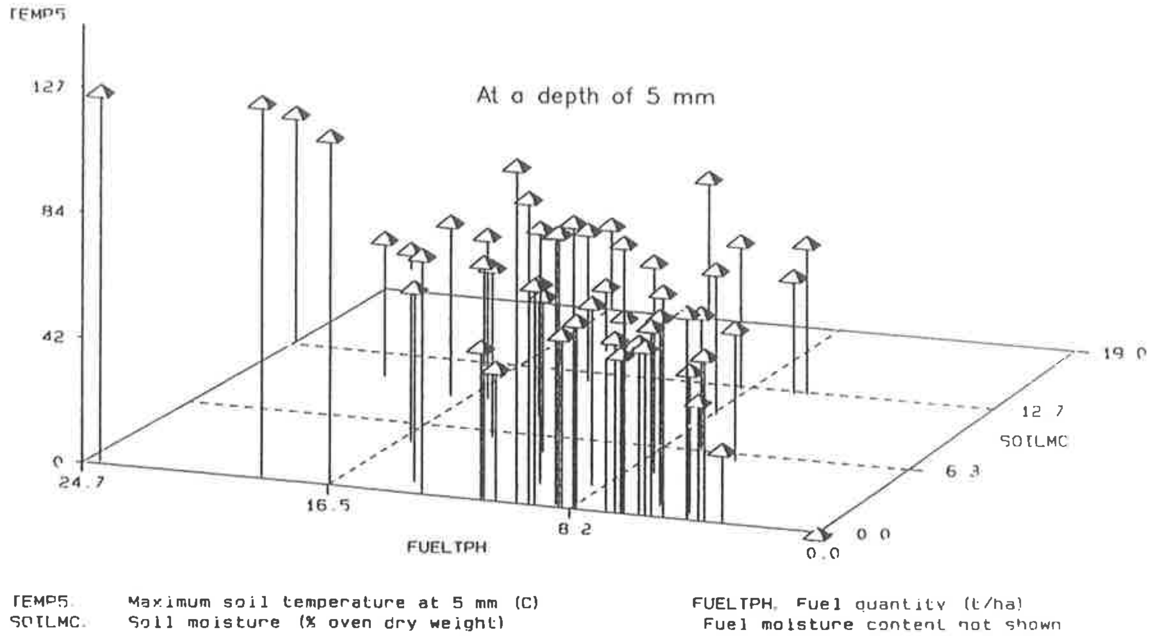
	Variable							
Variable	T_0	T_5	T_{10}	T_{15}	H_{L0}	H_{L5}	H_{L10}	H_{L15}
w_C	0.48	0.39	0.46	0.54	0.74	0.53	0.56	0.56
MC	0.14	-0.26	-0.40	-0.44	-0.24	-0.33	-0.33	-0.36
M_S	-0.01	-0.37	-0.37	-0.20	0.17	-0.36	-0.31	-0.26
r	0.22	0.28	0.13	0.10	-0.16	0.07	0.08	0.11
I	0.40	0.43	0.37	0.41	0.22	0.37	0.41	0.46
h_F	0.46	0.47	0.37	0.44	0.49	0.36	0.40	0.47
D	0.48	0.33	0.17	0.19	0.15	0.15	0.12	0.23
T_{AS}	0.21	0.39	0.40	0.36	0.13	0.35	0.35	0.36
T_5	0.46							
T_{10}	0.44	0.87						
T_{15}	0.41	0.74	0.93					
H_{L0}	0.35	0.60	0.68	0.70				
H_{L5}	0.37	0.86	0.87	0.80	0.75			
H_{L10}	0.38	0.81	0.87	0.83	0.73	0.97		
H_{L15}	0.39	0.80	0.88	0.89	0.75	0.94	0.96	

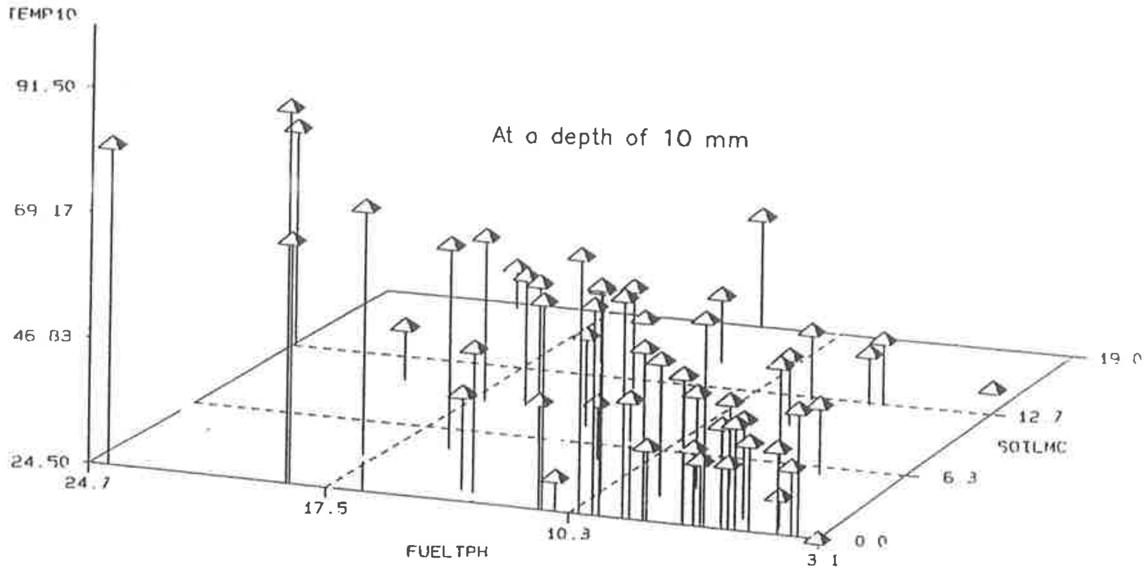
From Table 12-2, maximum soil temperature and heat load at various depths in the soil are strongly correlated with the quantity of fuel consumed (Pearson R^2 = 0.4-0.56) and weakly correlated with soil and fuel moisture content and with ambient soil temperature. Of the fire behaviour variables, soil heating shows some correlation with flame height and fire intensity, but is poorly correlated with rate of spread. The correlation between soil heating and flame height and fire intensity probably reflects multicollinearity between these variables and the quantity of fuel consumed and fuel moisture content. For example, the Pearson R^2 between fuel consumed and flame height is 0.71. Heat load is more dependent on fuel quantity consumed than is maximum temperature, reflecting the amount of heat energy released. Below the soil surface, there is strong correlation between maximum temperature and heat load, but the maximum temperature at the surface is weakly related to soil heating at depth (Table 1).

Maximum soil temperature and heat pulse are plotted with the quantity of fuel consumed and soil moisture content for the soil surface, and at 5 mm, 10 mm and 155 mm soil depths in Figure 12-3.

Figure 12-3: Maximum temperatures recorded by thermocouples set on the soil surface and at various soil depths, plotted with the quantity of fuel consumed by all phases of combustion and by soil moisture content.

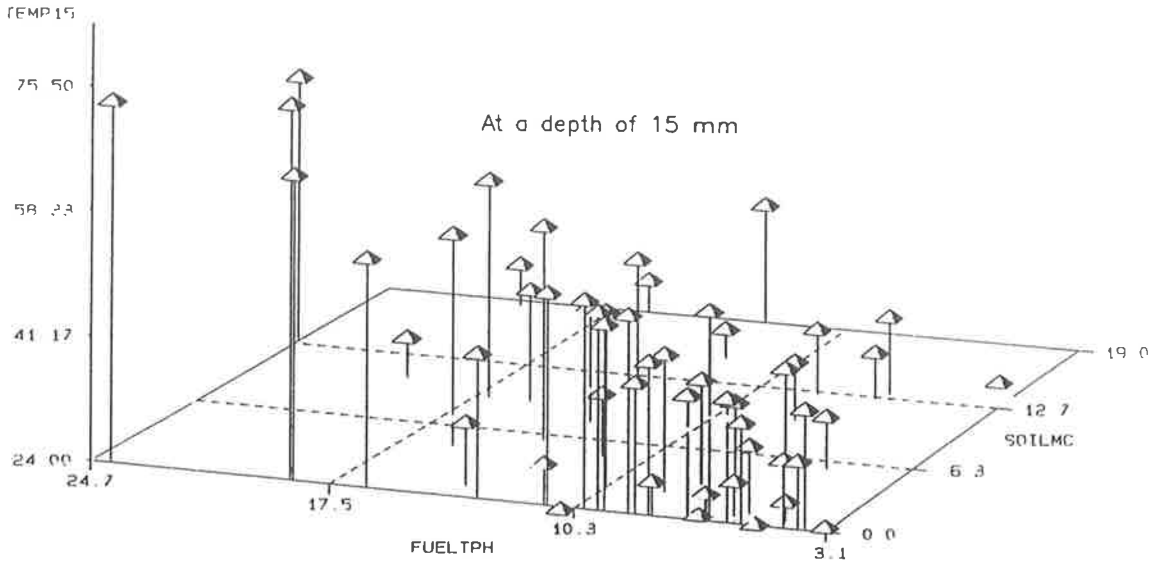






TEMP10 Maximum soil temperature at 10 mm (C)
SOILMC Soil moisture (% oven dry weight)

FUELTPH. Fuel quantity (t/ha)
Fuel moisture content not shown



TEMP15 Maximum soil temperature at 15 mm (C)
SOILMC Soil moisture (% oven dry weight)

FUELTPH. Fuel quantity (t/ha)
Fuel moisture content not shown

Correlation coefficients (Table 12-2) and the scatterplots in Figure 12-3 suggest that maximum soil temperature and soil heat load at various depths in the soil are related approximately linearly to the quantity of fuel consumed, fuel moisture content, soil moisture content and ambient soil temperature. With the exception of the regression for T_5 below, the contribution of ambient soil temperature to variation in temperature was slight (3-4%). Stepwise multiple linear regression analysis resulted in the following models to predict maximum soil temperature;

$T_5 = 2.45(w_C)+1.93(T_{AS})-1.93(M_s)+4.85 \quad R^2 = 0.54,$

$T_{10} = 1.76(w_C)+0.84(T_{AS})-1.23(MC)-1.24(M_s)+27.7 \quad R^2 = 0.68,$

$T_{15} = 1.63(w_C)+0.59(T_{AS})-1.37(MC)-0.72(M_s)+27.2 \quad R^2 = 0.68,$

where T_5, T_{10} and T_{15} = maximum soil temperature (°C) at 5 mm, 10 mm and 15 mm, w_C = quantity of litter fuel consumed (t ha^{-1}), T_{AS} = ambient soil temperature (°C), MC = fuel moisture content (% of odw), and M_s = soil moisture content (% odw - sandy soil).

From Figure 12-2 and work by Ashton and Gill (1976), Bristow *et al.* (1986) and others, the relationship between soil temperature and soil depth is nonlinear. Regression analysis incorporating a modified inverse function in soil depth and linear functions in fuel quantity consumed, soil moisture content and fuel moisture content, resulted in the following equation;

$T_{DX} = (219.6/(DX+0.62))+4.16(w_C)-0.87(MC)-3.05(M_s)+5.8$ (Equation 12-1),
(170.6) (0.03) (0.73) (1.0) (0.69) (12.8) (standard errors)
(Goodness of fit, S = 0.90)

where T_{DX} = maximum soil temperature (°C) at depth DX (mm) in the soil, DX = depth (mm) in the soil, w_C = quantity of litter fuel burnt to mineral earth (t ha^{-1}), MC = fuel moisture content (% odw.), M_s = soil moisture content (% odw.).

Observed maximum soil temperatures are graphed with those predicted using Equation 12-1 in Figure 12-4. Residuals, graphed in Figure 12-5, reveal patterns of model underspecification and of heterogeneous variation. The model seriously underpredicts soil temperature at the low end, when fuel quantity is very low and when soil moisture content is very high. The model also shows a poor capacity to predict temperature at the soil surface, which is to be expected as this is largely independent of soil conditions.

Figure 12–4: Maximum soil temperature predicted using Equation 12–1 with observed temperatures. The cluster of high temperatures are at the soil surface.

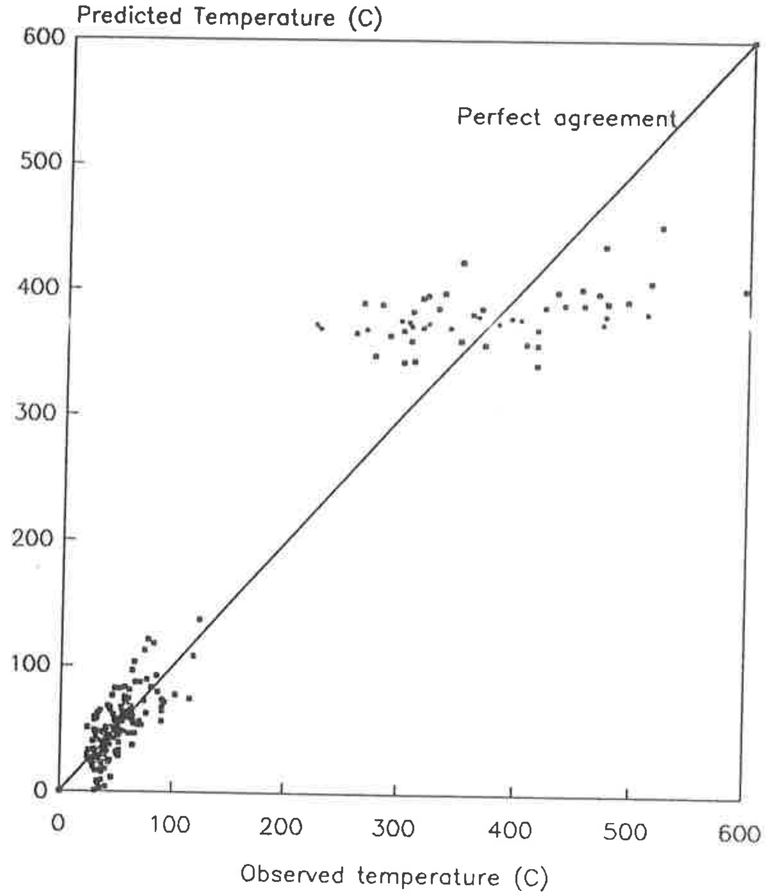
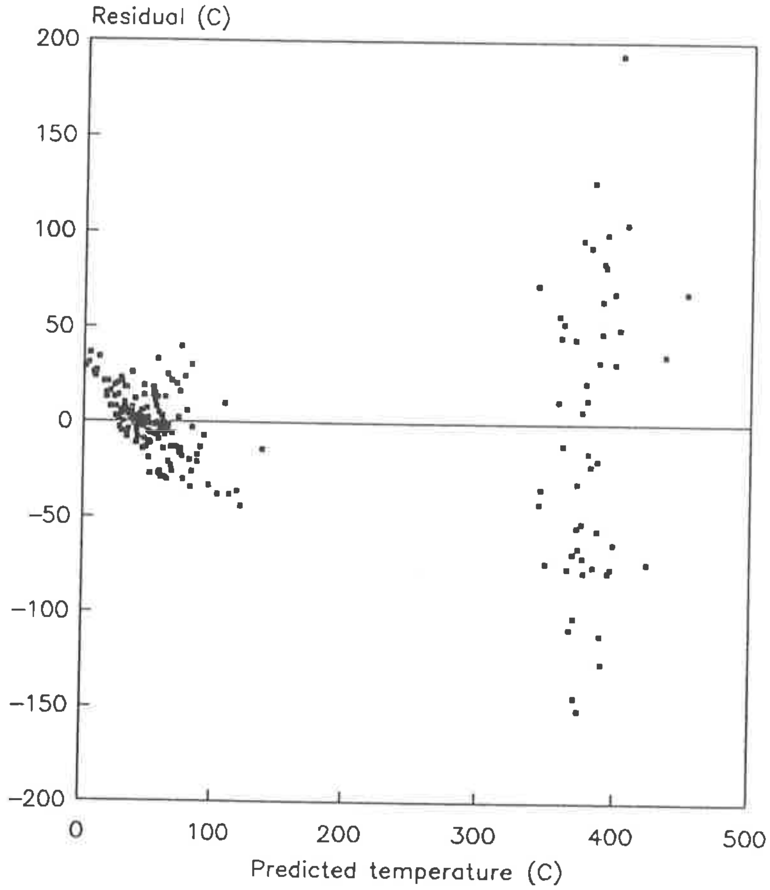


Figure 12–5: Residuals (Observed minus predicted soil temperatures) with predicted soil temperatures.



Heat load, the area beneath the temperature history trace, was also strongly related to soil depth, the quantity of fuel burnt to mineral earth and fuel and soil moisture content (heat load at the soil surface was independent of soil moisture content). The heat load measured at the soil surface was about double that measured at a depth of 15 mm. The highest heat load measured in the flames and 10 cm above the fuel bed during the study described in Chapter 7 was about eight times higher than the highest heat load measured at a depth of 15 mm in the soil. The linear regressions relating variables affecting heat load at various soil depths are;

$H_{L0} = 60.7(w_C)-38.7(MC)+504.6 \quad R^2 = 0.63$,

$H_{L5} = 44.8(w_C)-29.2(MC)-30.4(M_s)+335.0 \quad R^2 = 0.68$,

$H_{L10} = 38.6(w_C)-24.1(MC)-23.3(M_s)+235.4 \quad R^2 = 0.69$,

$H_{L15} = 30.4(w_C)-22.2(MC)-16.3(M_s)+179.4 \quad R^2 = 0.69$,

where H_{L0}, H_{L5}, H_{L10} and H_{L15} = heat load (degree min) at the soil surface, and at depths of 5 mm, 10 mm and 15 mm respectively.

The soil temperatures observed in this study fall within the wide range of temperatures reported during wildland fires by other authors (e.g., summaries by DeBano *et al.* 1977, Wells *et al.* 1979 and Dimitrakopoulos and Martin 1990). Most temperature data reported in the literature pertain to grass fires, with soil temperatures being generally lower than for forest fires. While there has been considerable interest in the very high soil temperatures experienced beneath burning piles of logs or other debris (e.g., Beadle 1940, Humphreys and Lambert 1965, Roberts 1965, Cromer and Vines 1966, Tunstall *et al.* 1976), there are few reports of soil temperatures experienced during fires burning in fine litter fuel of eucalypt forests, which is usually the dominant fuel type. Raison *et al.* (1986) reported mean maximum temperatures of 450 ^{o}C and 57 ^{o}C at the soil surface and at a depth of 2 cm respectively during experimental fires in *Eucalyptus pauciflora* forest under dry conditions and high fuel quantities. Shea *et al.* (1979) working in jarrah forests reported maximum soil temperatures of about 65 ^{o}C at 10 mm during a low intensity spring fire burning under moist fuel and soil conditions and 175 ^{o}C at 10 mm during a high intensity autumn fire burning under drier conditions. The temperatures reported by Shea *et al.* (1979) are significantly higher than temperatures recorded at the same depth during this study (Table 12-1), but there is likely to be considerable variation in the field associated with variations in fuel type and fuel quantity. By comparison, when soil and fuel were dry (<6%) and the quantity of fuel burnt was high (about 24 t ha^{-1}) the mean maximum temperatures recorded at the soil surface and at a depth of 15 mm in these laboratory studies were 486 ^oC and 78 ^oC respectively. Raison *et al.* (1986) studying soil temperatures during low intensity fires in a *Eucalyptus pauciflora* forest reported high temperatures (mean maximum of 57 ^oC at 2 cm) during the combustion of some 16 t ha^{-1} of litter fuel under dry conditions.

Forgeard (1989) recorded temperatures of 50-90 ^oC at 2.5 cm in the soil, and found that seeds in the soil survived this level heating. Giovanni *et al.* (1988) reported no soil structural changes up to temperatures of 220^o C. Beyond this, they reported loss of organic matter and loss of soil plasticity. Under normal fuel conditions in the jarrah forest, such high temperatures would not be reached in the soil, except immediately beneath burning logs or localised heavy fuel accumulations.

Soil heating during the burning of jarrah forest litter fuels in the laboratory is a function of the quantity of fuel burnt down to mineral earth, soil moisture content and fuel moisture content (Equation 12-1). These findings are similar to those of other authors (Humphreys 1969, Christensen and Kimber 1975, Shearer 1975, Ashton and Gill 1976, Wells *et al.* 1979, Ryan and Noste 1985 and Walker *et al.* 1986). The quantity of surface litter fuel consumed by fire affects soil heating since it represents the total energy released during combustion. Priestley (1959) determined that the rise in the soil temperature was proportional to the rate of heat supply and inversely related to the conductive capacity of the soil. Physical modelling and laboratory studies using artificial heat sources have further added to our understanding of this process (e.g., Aston and Gill 1976, Steward *et al.* 1989).

The fraction of the fuel bed burnt and the maximum fuel particle size burnt will depend on fuel moisture content and on wind speed (Rothermel 1972, Cheney 1981, Stocks 1989). Unlike the controlled fuel conditions in these laboratory experiments, surface fuel particle size in the jarrah forest ranges from small twigs to logs in excess of 1 m in diameter (Chapter 5). Fuel quantity and particle size affects both the duration of heating (flame residence time and burn out time) and the amount of heat released. Logs and limbs lying on the forest floor represent a very high but localised fuel quantity, and when dry, logs burn for long periods, sometimes days. Extremely high soil temperatures have been recorded beneath logs. Humphreys and Lambert (1965), Cromer and Vines (1966) and Cromer (1967) have recorded temperatures of up to 666 ^oC just below the soil surface and 112^o C at 22 cm. Longer combustion times and the concentration of high fuel quantities associated with branches and logs results in higher soil temperatures for a longer duration and at a greater depth than for by the combustion of fine litter fuels (6 mm diameter). Floyd (1966), investigating soil temperatures under three different fuel types, found that temperatures were higher for longer periods with increasing fuel particle size. The high spatial variation in soil heating measured during forest fires (Christensen and Kimber 1975 and Raison *et al.* 1986) is in part due to variations in the quantity of fuel burnt and the particle size of burning fuels.

The depth of burn, or the fraction of surface fuel burnt, also affects soil heating (Wells et al. 1979), because it reflects both the quantity of fuel burnt and the proximity of combustion in relation to the soil surface. Depth of burn has burn used to descriptively characterise the intensity or severity of fire in relation to soil heating, particularly in North American vegetation types (e.g., Tarrant 1956, Bentley and Fenner 1958 and Wells *et al.* 1979). During this study, depth of burn was not variable as fuel moisture conditions were such that the fuel bed was consumed down to mineral earth. However, in situations where litter fuels are deep (>25 mm), a strong moisture gradient can exist through the profile of the litter bed such that the surface fuel is dry but fuels at depth and near the soil surface are wet. Under mild weather conditions, only the dry surface fuels may burn (Peet 1965 and Lawson *et al.* 1985) resulting little heating of the soil.

Low intensity (<350 kW m^{-1}) fuel reduction burns in the forests of the south-west of Western Australia are normally carried out in spring when the top 10-15 mm of the litter layer are moist (12-15%) and the deeper litter profile and soil are wet (>25% odw). This results in the combustion of the surface fuel, but the fuel near the soil surface is usually unburnt or charred. Shea *et al.* (1979) have shown that soil heating during a spring burn in a jarrah forest was slight, with heat rarely penetrating more than 5 mm below the soil surface. They concluded that the poor regeneration of legumes following such fires in the northern jarrah forest could be attributed to low soil heating. Soil and seedbed conditions following fire have been shown to be influenced by the proportion of surface fuel burnt (Heyward 1938, Chrosciewicz 1974, Shearer 1975, Miller 1977, Humphreys and Craig 1981, Hungerford 1987 and Burrows *et al.* 1991).

Fuel moisture content is important because it affects the quantity of fuel consumed and the reaction intensity of the fire, as energy is required to evaporate moisture from fuels before pyrolisis and ignition can occur. Frandsen and Ryan (1986) reported that soil temperatures and heat load were significantly reduced by the presence of moisture in the duff layer of the litter bed and in the soil. This is consistent with the findings of this study and the predictive relationships presented here allow the relative importance of fuel moisture content (for jarrah forest litter fuels) to be determined (Equation 12-1).

Soil water, or soil moisture content for a uniform soil type, is the most important soil property affecting the rate of heat transfer (see Aston and Gill 1976 and reviews by Wells *et al.* 1979 and Humphreys and Craig, 1981). Nakshabandi and Kohnke (1965) found that soil moisture had a much greater effect on thermal conductivity of soils than bulk density and grain size. Moist soils have higher thermal conductivities (Priestley 1959 and Nakshabandi and Kohnke 1965) and higher specific heat contents. Energy is used to evaporate moisture and while wet soils will take up and release heat more readily than dry soils, they show poorer temperature response (Priestley 1959, De Vries 1963 and Aston and Gill 1976). Soils vary considerably in structure, but these variations do not affect heat transfer as much as soil moisture. Aston and Gill (1976), using synthetic heaters in the laboratory, compared soil heating in clay and sand soils and found that the lower thermal conductivity of clay resulted in consistently lower temperatures, but soil type was not as important as soil moisture. Portlock *et al.* (1990), using gas heaters in the laboratory, found that temperatures reached in a gravelly jarrah forest soil were not significantly different to those in a sand soil and that soil moisture was more important. Water has a high heat capacity, so soil temperatures do not rise above 100 °C until the water has been driven off (DeBano *et al.* 1976, 1979).

There is little reported information about the effects of heat load on the biophysical properties of soil, with maximum temperature most commonly used to characterise soil heating. Maximum soil temperature and heat load were closely related for the fuel used during these experiments (Table 12-2) but this is probably not the case for larger fuel particles such as burning logs. Walker *et al.* (1986) summarised the literature dealing with various changes in biological, physical and chemical aspects of soil in relation to temperature. They found that biological changes take place up to a temperature of about 120 °C when sterilization takes place, chemical changes take place by about 600 °C, and physical changes occur over 600 °C. Temperatures experienced below the soil surface during the combustion of fine jarrah litter fuels are unlikely to approach the high temperatures which cause significant chemical and physical changes, but they are within the range likely to cause biological changes.

12.4 Concluding discussion

The empirically derived soil heating model developed by this study (Equation 12-1) provides a unique quantitative relationship between fuel, fire and soil characteristics which can be used to characterise the severity of jarrah forest fires in relation to the soil. Variables affecting soil heating viz., the quantity of fuel consumed, fuel moisture content and soil moisture content, can now be considered quantitatively when prescribing fire to stimulate the germination of soil stored seed or to evaluate the impact of fire on the soil. The model could be used directly to predict soil heating under standard soil and fuel conditions, (conditions similar to the experimental conditions), and it can be used as a biological index of soil heating.

Work by Shea *et al.* (1979) and Majer (1982) has shown that most viable seeds of *Acacia pulchella*, a legume widely distributed throughout the jarrah forest, occur in the top 3 cm of the soil. Laboratory studies by Portlock *et al.* (1990) showed that the best germination response for *Acacia pulchella* seeds occurred when seeds were heated between 60 ^{o}C and 130^{o} C for between 10-30 minutes. They also reported that while dry soil heated quicker than moist soil, soil moisture *per se* did not affect germination. Martin and Cushwa (1966) reported that, in the laboratory, dry heat did not increase the germination of *Cassia nictitans*, but moist heat had a pronounced affect on the total germination rate. Similar results were reported by Aveyard (1968) for six *Acacia* species tested in the laboratory. Warcup (1980) also reported improved germination of soil stored seed following heat treatment.

Based on the findings of this study and on biological studies in the jarrah forest (Shea *et al.* 1979 and McCaw 1989), the dense legume regeneration often observed after summer and autumn wildfires is largely due to complete consumption of the surface fuel, dry soil and dry fuel. Byram's fire intensity and fire rate of spread are important only in as much as they may relate to or affect the quantity of fuel consumed. Post-fire weather conditions, especially rainfall, are important in determining the time of germination, density and survival of seedlings (Bell *et al.* 1989, Burrows *et al.* 1991).

The predictive relationships developed in this study can be used as guides to prepare prescriptions, to implement managed fires to regenerate legumes for disease control or to regenerate habitat on appropriate sites in the jarrah forest. Fast spreading, intense fires which are difficult to implement and which are likely to cause damage to other forest values, are not necessary to heat the soil. Clearly, increased soil heating will be achieved by burning when the fuel and soil are dry in summer or autumn and by burning high fuel loadings.

Soil temperature predictions made for a standard soil depth can be interpreted as a soil heating index or an index of the biological impact of fire on the soil. Such an index would enable fire managers and fire ecologists to characterise a fire according to its impact on topsoil. It would also provide a quantitative means of evaluating and comparing fires. A linear regression model (Equation 12-2) for predicting soil temperature at a depth of 10 mm during a fire from w_C, MC and M_s is proposed as a Soil Heating Index. The fitted regression is;

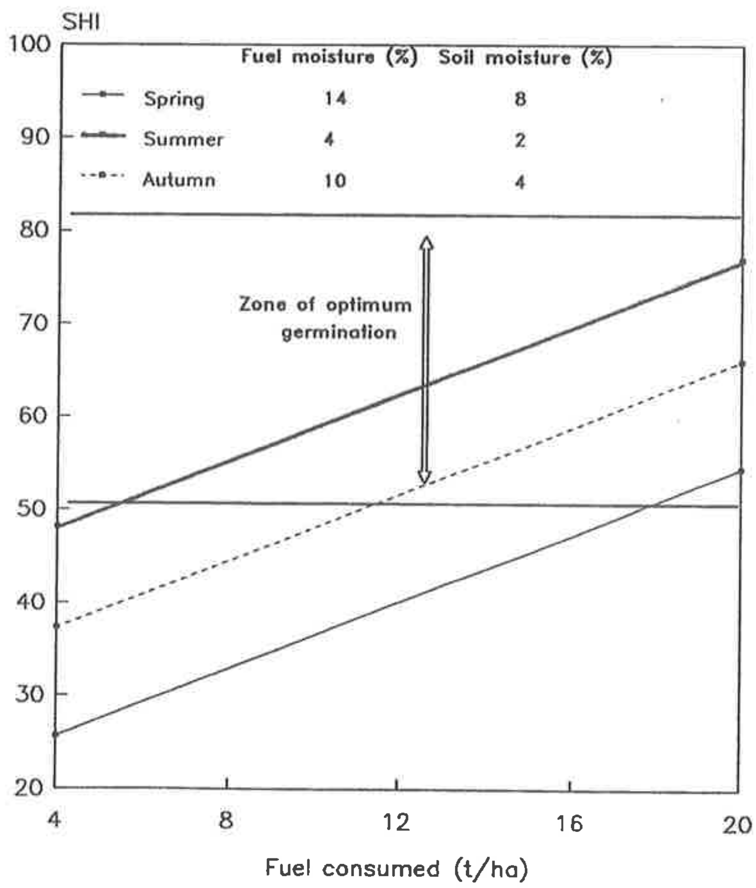
SHI = $1.8(w_C)-1.6(MC)-1.3(M_s)+51.3$ $R^2 = 0.69$ (Equation 12-2),

(0.23) (0.36) (0.21) (4.3) (standard errors)

where SHI = Jarrah forest Soil Heating Index (or the predicted soil temperature (^{o}C) at 10 mm in standard soil type), w_C = quantity of litter fuel consumed down to mineral earth, MC = fuel moisture content, M_s = soil moisture content (to 10 mm).

Knowing that most legume seed occurs in the top 10 mm of the soil and that seeds need to be heated to 50-90 °C for optimum germination to occur (Christensen *et al.* 1981 and Portlock *et al.* 1990) this index can be used as a guide to planning fires to regenerate legume thickets (see Figure 12-6). This does not take account of soil heating by other coarse scattered fuel pieces such as branches, logs, bark, and live and dead aerial vegetation. Used in conjunction with the fire behaviour prediction model developed in Chapter 8, fire managers can plan and execute prescribed burns to regenerate soil stored seed with a degree of confidence. The likelihood of litter bed fires injuring or killing mature, deep subterranean organisms such as lignotubers, or destroying buried seed, or causing physical changes to the soil, is remote due to the insulating properties of soil. The impact of fires set under moist soil and fuel conditions on the soil is likely to be negligible. Examples of the soil heating index values (or the predicted soil temperature at 10 mm under standard fuel and soil types) for various combinations of fuel and soil moisture are presented in Figure 12-6.

Figure 12–6: Soil Heating Index (SHI) or the predicted soil temperature at a depth of 10 mm. The range for optimum germination of legume seed at 10 mm is shown. Temperatures will be higher at shallower depths.



CHAPTER 13

A JARRAH FOREST FIRE MODEL

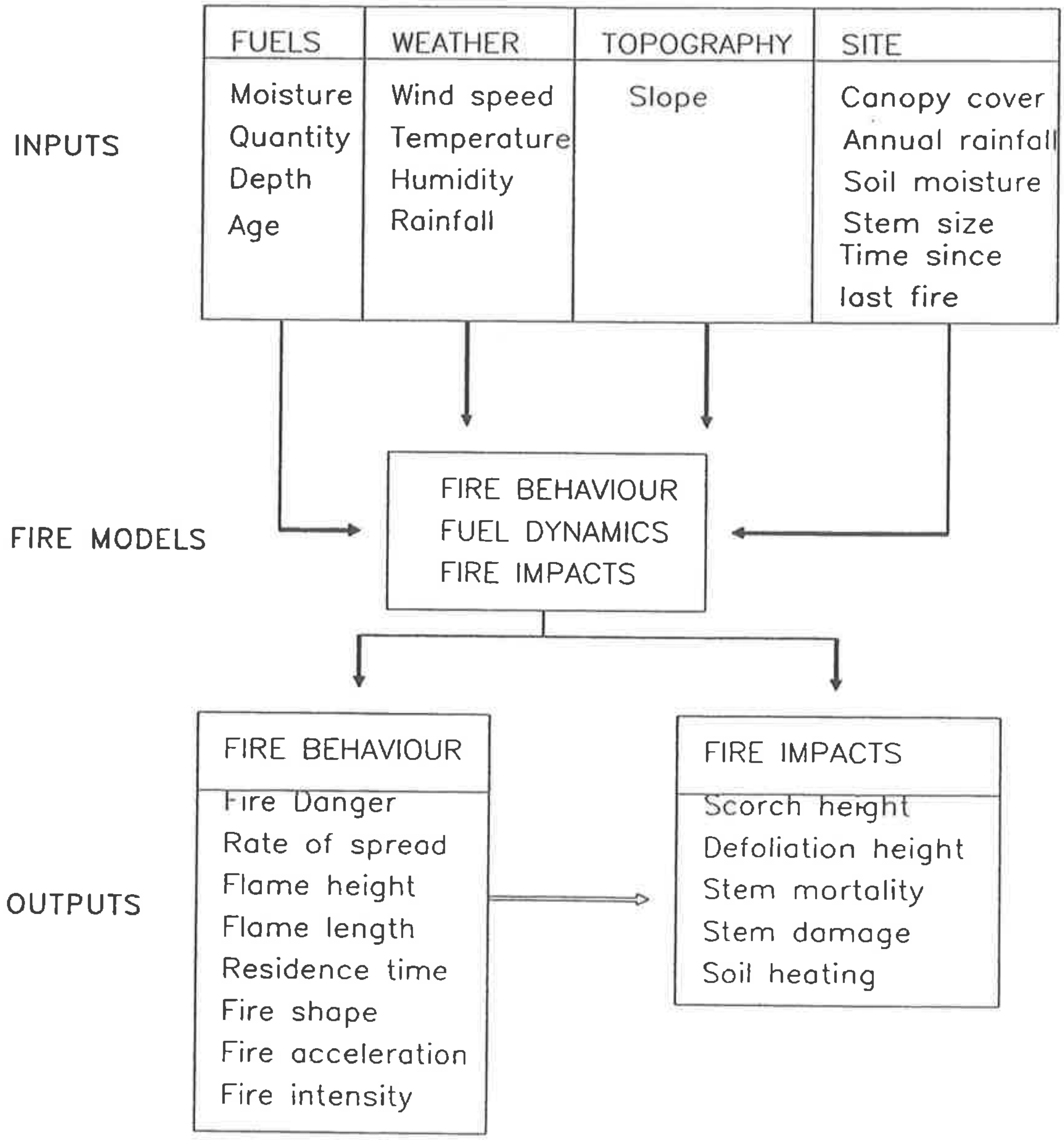
13.1 Model structure

The development, use and limitations of existing eucalypt forest fire models were discussed in detail in Chapter 4. Briefly, the Forest Fire Behaviour Tables for Western Australia (FFBT) (Sneeuwjagt and Peet 1979, 1985) were designed to forecast fire danger and to predict rate of spread in six major forest fuel types in the south-west of Western Australia. The rate of spread prediction component of the FFBT (1979 version) is based on small, low intensity experimental fires in standard jarrah forest and karri forest fuel types. The rate of spread in standard jarrah fuel and on level terrain represents the Jarrah Forest Fire Danger Index (FDI) and various correction factors are applied to the FDI to predict rate of spread in other fuel types and on sloping terrain. With the exception of scorch height, the FFBT do not make predictions of the acute impacts of fire which give rise to important ecological responses or commercial losses.

The preceding chapters describe the experimental development of models for predicting jarrah forest fire behaviour and some important acute impacts over a wide range of potential burning conditions. This chapter presents a structure linking these models to form an integrated fire behaviour and impact prediction system.

The structure of the jarrah fire model is shown in Figure 13-1. Inputs are either measured directly or are determined indirectly from i) weather forecasts ii) sub-models developed in this thesis or iii) the FFBT. Beck (1994) developed equations from the tabulated data in the FFBT (1985 version). These equations are referred to when predicted input parameters are required to derive the FDI but which are not dealt with in this thesis. In particular, the FFBT provide a method for determining fuel moisture content from weather variables and for adjusting open (standard exposure) wind speeds to wind speeds at 1.5 m in the forest.

Figure 13–1: Structure of the jarrah forest fire behaviour and fire impact model.



13.2 Forecasting fire danger and predicting fire behaviour

13.2.1 FDI and rate of spread

Surface fuel moisture content (SMC) and wind speed are used to predict rate of spread in standard jarrah fuel and on level or gently undulating terrain. This also represents the FDI. SMC, the moisture content of the top 10 mm or so of the fine litter fuel, can be measured directly or estimated using procedures described in the FFBT. Wind speed is measured at 1.5 m in the forest; the FFBT provide guide-lines for reducing forecast open wind speeds. The FDI for standard jarrah forest fuel is calculated by;

$FDI = 23.19 * SMC^{-1.495} * U^{2.674} + 11.60$ (Equation 8-1).

Where;

FDI = Fire Danger Index, or the rate of spread (m h^{-1}) in standard jarrah fuel (SJF) and on level or gently undulating terrain

SMC = surface fuel moisture content (% odw)

U = wind speed at 1.5 m in the forest (km h^{-1})

Application bounds

$3 < SMC < 21$

$0 < U < 9$

To predict rate of spread, the FDI is adjusted for slope by;

$r_F = FDI * e^{(0.0687*S)}$ (Equation 7-9).

Where;

r_F = rate of spread (m h^{-1})

FDI = Fire Danger Index

S = slope (degrees)

Application bounds

$14^o < S < +14^o$

Equation 7-9 above, which adjusts rate of spread for sloping terrain, applies to zero wind conditions. The relationship is only valid when wind and slope are aligned. The Canadian Forest

Fire Behaviour Prediction System (CFFBPS) (Forestry Canada 1989) deals with slope-wind interaction by converting the influence of slope on rate of spread to an equivalent wind speed and then determining the net combined effects of wind and slope by vector resolution. The relatively straight forward mathematical steps in this process are described in the CFFBPS (Forestry Canada 1989) and could apply equally well to the jarrah forest.

The FFBT adjusts rate of spread according to available fuel quantity (see Chapter 4). The experiments reported in this thesis (Chapters 7 and 8) failed to show any relationship between headfire rate of spread and fuel quantity per unit area. The quantity and composition of standard jarrah forest fuel changes with time since last fire (Chapters 5 and 6); it is possible that structural and composition changes, rather than fuel quantity, significantly affects rate of spread. The effects of fuel structure on the behaviour of eucalypt forest fires is an important area of research requiring further investigation.

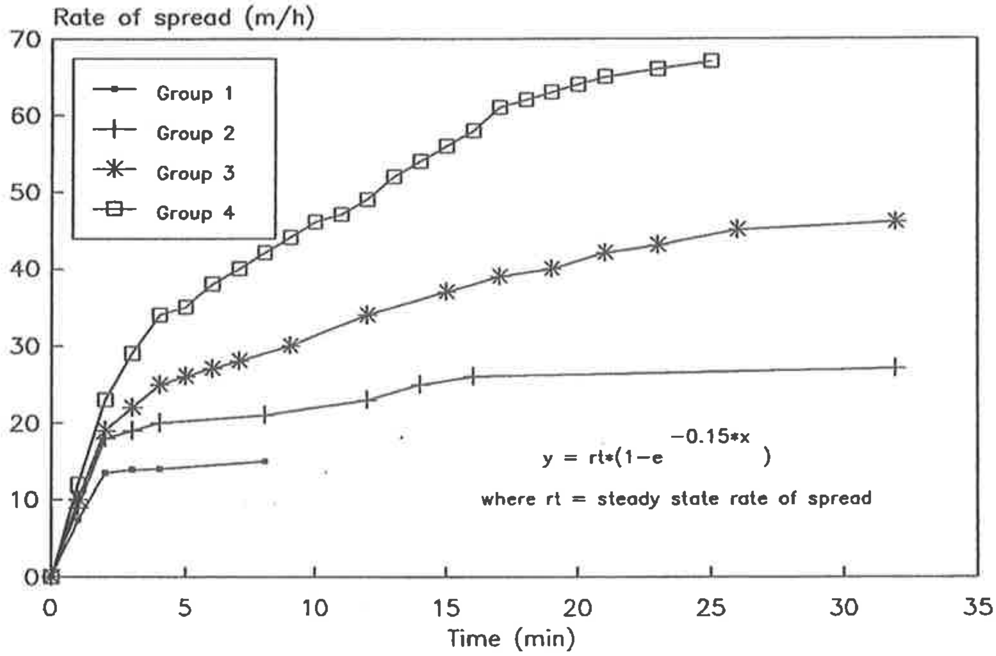
13.2.2 Fire acceleration

Rate of spread derived using Equations 8-1 and 7-9 represents a steady state or equilibrium rate of spread. Fires developing from a point source progress through a build-up phase before reaching a "quasi-steady state". There is general agreement on the form of the relationship between rate of spread and time elapsed since ignition (e.g., Cheney and Barry 1969, Luke and McArthur 1978, McAlpine 1988 and Weber 1988). The form of this relationship for jarrah forest fuels was examined using fire isopleth maps constructed by George Peet (archived at the CALM Science and Information Division Office in Manjimup). Only fires which had reached equilibrium were included in analysis. Firstly, fires were grouped according to equilibrium rate of spread, then for fires within a group, the mean rate of spread at time "t" after ignition was graphed with time "t" (Figure 13-2). The following regression was fitted to Peet's data shown in Figure 13-2.

$r_{tx} = r_F*(1-e^{-0.149*t})$ (Equation 13-2)
(0.0055) (parameter standard error).

Where;
r_{tx} = rate of spread at time "x" after ignition (m h^{-1})
r_F = steady state rate of spread (m h^{-1})
t = time after ignition (min.)

Figure 13-2: Mean rate of spread with time since ignition for point source fires in jarrah fuels (Source: Peet unpubl. data, CALM archives, Manjimup).



13.2.3 Litter fuel accumulation

Litter fuel consists of twigs, leaves, bark and floral parts < 6 mm in diameter which accumulate on the forest floor. It is the dominant fuel component. The quantity of litter consumed by fire (available fuel) will affect flame height, fire intensity and some fire impacts, and is a function of the total fuel quantity and fuel moisture content. The mean quantity of litter fuel in a standard jarrah forest fuel type can be estimated by:

i) Biomass sampling

ii) Measuring the depth of the fuel bed and applying the equation;

$$w_T = 0.406*f_D.$$

Where;

w_T = total litter fuel quantity (t ha^{-1})

f_D = depth of litter bed (mm).

iii) Using predictive equations;

w_{T50} $= 15.6(1\text{-}e^{-0.16*t})$ (rainfall > 950 mm annum^{-1}) (Equation 5-1)

w_{T35} $= 11.1(1\text{-}e^{-0.17*t})$ (rainfall > 950 mm annum^{-1}) (Equation 5-4)

w_{T35} $= 8.10(1\text{-}e^{-0.18*t})$ (rainfall < 950 mm annum^{-1}) (Equation 5-5).

Where;

w_{T50} = total litter quantity; canopy cover 45%-55% (t ha^{-1})

w_{T35} = total litter quantity; canopy cover 30%-40% (t ha^{-1})

t = time since last fire (years).

Litter fuel quantity beneath bull banksia thickets can be as much as 50% higher than the mean value, and beneath sheoak thickets, 100% higher than the mean value.

13.2.4 Flame height and length

Flame height is predicted from rate of spread and the quantity of fuel consumed, or the available fuel quantity. Available fuel is the proportion of the total fuel that is available to burn (or is burnt) in a fire (Sneeuwjagt and Peet 1979, 1985) and can be measured directly (by measuring fuels before and after fire) or estimated from the moisture content of the litter fuel bed. In most jarrah forests, the litter fuel bed is rarely deep enough for a strong moisture gradient to exist throughout the profile. Where deep litter fuels (> 20 mm) occur, then the available fuel can be estimated from the surface and profile fuel moisture contents, using tables provided in the FFBT. Beck (1994) has reduced these tables to equations to enable the quantity of fuel consumed by fire (available fuel) to be readily estimated. Flame height is predicted using Equation 8-3:

h_F $= 0.003355 r_F^{0.8259} * w_C$ (Equation 8-3).

Where;

h_F = headfire flame height (m)

r_F = rate of spread (m h^{-1})

w_C = fuel consumed (or available fuel) (t ha^{-1}).

Application bounds

$14 < r_F < 1,000$

$4 < w_C < 19$

Flame length is predicted from fire intensity using Equation 8-5:

$L = 0.0147*I^{0.0767}$ (Equation 8-5).

Where;

L = flame length (m)

I = Byram's fire intensity (kW m^{-1}).

Application bounds

$50 < I < 4,500$

13.2.5 Fire Intensity

Fire intensity is calculated by;

$I = r_F*w_C*0.52$,

or estimated from flame length by,

$L = 293.8*I^{1.118}$ (Equation 8-6).

13.2.6 Flame residence time

In the field, flame residence time is determined from rate of spread and flame depth (see Cheney 1981), or can be measured using temperature sensors (Gill and Knight 1991), or estimated from the quantity of fine litter fuel consumed. For standard jarrah fuel, the relationship is;

$t_r = 5.4*w_C$.

Where;

t_r = flame residence time (s)

w_C = litter fuel consumed (t ha^{-1}).

13.2.7 Fire shape

A fire originating from a point source and burning in homogeneous fuel and under the influence of a constant wind assumes a more-or-less elliptical shape (Chapter 7). The length-to-width ratio characterises the fires elliptical shape and can be estimated from:

$L/W = 1.0+0.0236*U^{2.114}$ (Equation 7-10).

Where;

L/W = length-to-width ratio

U = wind speed at 1.5 m in the forest (km h^{-1}).

Application bounds

$0 < U < 9$.

13.3 Predicting Acute Fire Impacts

The combustion of live and dead vegetation and heating of vegetation and soil during a bushfire gives rise to biological responses and in some circumstances, commercial losses. Fire must be appropriately characterised according to its acute impact on the biota if forest scientists and managers are to use fire to achieve desired ecological outcomes, or to evaluate the ecological or commercial impact of fire. This thesis provides a meaningful way of doing this based on empirically derived models for three impact zones.

13.3.1 Impact above the flames: Scorch height

Scorch height is a function of fire intensity, ambient temperature and wind speed. Van Wagner's (1973) semi-empirical scorch model was regressed with jarrah forest scorch data and the following equation derived;

$$S_h = 1.49 \left[\frac{0.742\,(I)^{1.166}}{(60 - T_A)\,[0.0256(I) + (0.28U)^3]^{0.5}} \right] + 1.86 \qquad R^2 = 0.65$$

Where;

S_h = maximum scorch height (m)

I = Byram's fire intensity (kW m^{-1})

T_A = ambient air temperature (^oC)

U = wind speed in the forest at 1.5 m (km h^{-1}).

Application bounds

$50 < I < 4,500$

$20 < T_A < 38$

$2 < U < 9$

Scorch height can also be readily predicted from flame height and fire intensity for various seasons in which the fire is burning;

$S_h = 15.36*(h_F)^{0.8}\ e^{TA(-0.013)}$

$S_{hs} = 4.92*h_F+0.49$

$S_{hs} = 5.6*h_F$ (no intercepts model)

$S_{ha} = 8.53*h_F+2.03$

$S_{ha} = 9.4*h_F$ (no intercepts model)

$S_{ha} = 0.28*(I)^{0.58}$

Where;

S_h = scorch height all seasons (m)

S_{hs} = scorch height, cool moist spring conditions (SDI < 1,000) (m)

S_{ha} = scorch height, warm dry summer/autumn conditions (SDI > 1,000) (m)

h_F = flame height (m)

I = Byram's fire intensity (kW m^{-1})

T_A = ambient temperature (°C)

13.3.2 Impact in the flames: Stem death and injury

For surface fires, potential flame defoliation height is equivalent to flame height. Under severe conditions, localised crowing and torching can result in total defoliation of mature forest. Field observations suggest that intermittent crown fire in mature jarrah forest occurs at intensities above about 5,000 kW m^{-1} (see McCaw *et al.* 1992).

Stem death and injury is a function of bark thickness (or stem diameter), the quantity of fuel consumed and fire intensity. Jarrah and bull banksia stems of similar diameter have similar bark thickness and even though their barks differ structurally, the following equations predicting stem mortality can apply to both species.

$$BT_M = 0.78*(w_C)$$

$$P_M = 0.6+7.2*10^{-4}*(I)-5.1*10^{-2}*(DOB).$$

Where;

BT_M = minimum thickness of bark for a stem to survive fire (mm)

w_C = litter fuel consumed

P_M = probability of a stem being killed by fire

I = fire intensity (kW m^{-1}).

Application bounds

$4 < w_C < 19$

$50 < I < 1{,}500$.

Jarrah and marri trees most prone to fire-caused stem damage are small trees (< 20 cm dbhob), trees with old injuries which have not fully occluded, coppice stems (resprout stem growing off a stump), and trees near (< 2 m) coarse woody debris such as logs. Damage on the leeward side of a stem caused by the "chimney effect" is a function of bark thickness (stem diameter) and fire intensity. The probability of a stem being damaged by fire is shown in Table 11-6.

13.3.3 Impact below the flames: Soil heating

Jarrah forest plant species have evolved a wide variety of physical and biological traits which enable them to persist in a fire-prone environment. About 70% of plants resprout following fire and about 30% of plants regenerate from seed stored either in the canopy or in the soil (Christensen and Kimber 1975). Many resprouter species (particularly shrubs) also have a soil store of seed. Vlahos and Bell (1986) reported that the total germinable soil seed store in northern jarrah forest is as high as 1,579 seed m^{-2} with species richness being as high as 45 species m^{-2}. Fire-induced soil heating, or heat shock, often stimulates massive germination of soil stored seed, particularly of members of the Papilionaceae and Mimosaceae (see review by Bell *et al.* 1993). Best germination occurs when seeds are heated to 50-90 ^{o}C (see Chapter 12). Dense legume thickets improve forest fertility, and on some sites, provide important food and shelter for a number of rare animal species (see Chapter 12). The following models provide the first quantitative understanding of soil heating during jarrah forest fires which allow managers to numerically evaluate and characterise fires in terms of soil heating.

$T_{DX} = \{219.6/(DX+0.62)\}+4.16*(w_C)-3.05*(M_s)-0.87*(MC)+51.3$ (Equation 12-1)

$SHI = 1.8*(w_C)-1.3*(M_s)-1.6*(MC)+51.3$ (Equation 12-2).

Where;

T_{DX} = soil temperature at a depth of DX mm (^oC)

SHI = Soil Heating Index, or the predicted soil temperature at a depth of 10 mm in sandy soil

DX = depth in the soil (mm)

w_C = fuel consumed to mineral earth

M_s = soil moisture content to depth DX (% of odw)

MC = litter fuel moisture content (% of odw)

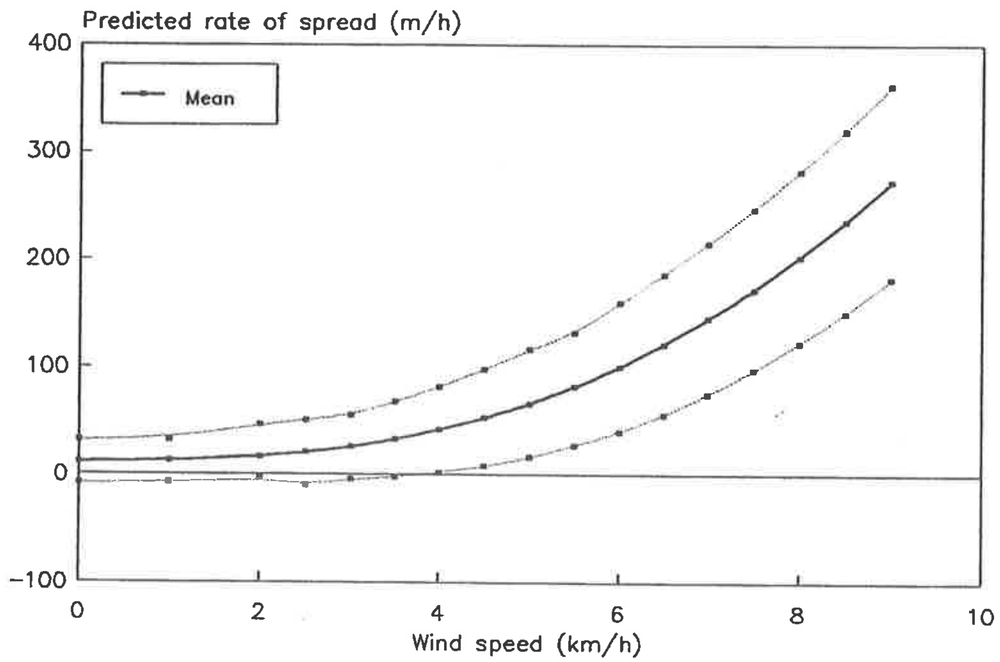
13.4 Reliability of model predictions

The regression models described above predict fire behaviour and some important fire impacts from experimental data gathered either in the laboratory or in the field. Selection of the appropriate model from a group of possible models was based on a balance of practical knowledge of fire behaviour and fire impacts and on statistical criteria, such as correlation coefficient (R^2), estimate of error variance (s^2), bias and precision (after Myers 1989).

Clearly, fire behaviour and impact prediction is very important for fire managers and fire scientists. Equally important to model users is a knowledge of the quality of prediction. As discussed in Chapter 4, empirically derived models perform best over the range of experimental conditions (application bounds) under which they are developed. Models developed in this thesis and the associated error statistics enables users, for the first time, to define prediction intervals, or the bounds within which an observation can be expected to fall. An example of 70% prediction intervals on predicted rate of spread for a fuel moisture content of 10% are graphed in Figure 13-3.

Aside from the unexplained variation in dependent fire behaviour and impact variables, accuracy of prediction will also depend on the accuracy with which model input parameters are measured or forecast. Trevitt (1991) used McAthur's Forest Fire Danger Meter to demonstrate how relatively minor uncertainties in wind speed and fuel moisture content result in considerable uncertainty in predicted rate of spread, particularly at low moisture contents and high wind speed. Headfire rate of spread is highly sensitive to wind speed, especially when fuel is dry. Further research into wind flow through forests and over variable terrain is needed to improve the quality of fire behaviour prediction. The FDI equation developed in this thesis relates to a wind speed measured at 1.5 m above the ground and in the forest. Operationally, wind speed measurements and forecasts are made for a standard exposure (10 m above ground and in a cleared area or 15 m above the forest canopy). Improved procedures and more sensitive anemometers are required so that fire managers can obtain accurate estimates of wind speed at 1.5 m in the forest.

Figure 13-3: 70% prediction intervals on predicted jarrah headfire rate of spread for a fuel moisture content of 10%.



13.5 General Conclusions

Jarrah forest fire management involves controlling wildfires and using prescribed fire to achieve clearly defined management objectives. There is a growing requirement to apply prescribed fire over a wide range of fuel and weather conditions for a variety of purposes, including fuel reduction, regenerating specific plants, eradicating plants, and creating floristic and structural diversity. A firm knowledge of fire behaviour over a wide range of burning conditions, acute physical impact of fire and of the long term effects of fire is necessary to plan and implement appropriate fire regimes and suppression strategies. Jarrah forest fire behaviour models developed in the 1960s are adequate for planning and implementing low intensity fires for fuel reduction, but are inadequate for planning, implementing and evaluating fire regimes for multi-purpose management of jarrah forests.

This thesis describes the experimental and statistical development of models for predicting fire behaviour and fire impact in jarrah forest fuels over a wide range of burning conditions. Fire behaviour and factors affecting heat release and heat transfer are coupled with some physical impacts of fire which give rise to biological responses important to current and foreseeable management of the jarrah forest.

The Forest Fire Danger Index (FDI) is the primary input for predicting headfire rate of spread using the Forest Fire Behaviour Tables for Western Australia (FFBT). The FDI is the headfire rate of spread expected in a standard northern jarrah forest litter fuel bed (7.2-8.4 t ha^{-1}) and on flat terrain and is a function of wind speed and fuel moisture content.

Two Australian forest fire behaviour models, the FFBT (1979 edition) and McArthur's Mk V Forest Fire Danger Meter, developed from small, low intensity fires, seriously underpredict rate of spread in standard fuel at low moisture contents and high wind speeds by a factor of about 2. Both models assume a direct linear relationship between fuel quantity and headfire rate of spread, so predictions are adjusted according to fuel quantity. In this thesis, backfire rate of spread was found to be dependent on fuel quantity, but headfire rate of spread was independent of fuel quantity per unit area. Wind driven fires spread quickly across the litter fuel bed surface, with fuels lower in the profile being consumed behind the leading edge of the flaming zone and often by secondary combustion phases. The high packing ratio of jarrah forest litter bed fuel limits the rate of vertical fuel consumption at the leading edge of the flaming zone. The composition and structure of jarrah forest fuel varies with time since fire (fuel age) and the effect of these changes on headfire rate of spread requires further investigation.

Headfire rate of spread in standard jarrah fuel and on level terrain is a power function in wind speed and in fuel moisture content. This equation form was the best model choice for the experimental conditions, but may over-estimate rate of spread on extrapolation to low moisture contents and very high wind speeds (> 10 km h^{-1} at 1.5 m in the forest). Wildfire observations in jarrah forest litter bed fuel suggest that the relationship between rate of spread and wind speed may be sigmoidal, but verification of this under experimental conditions is likely to be too dangerous to attempt. The behaviour of forest fires burning under fuel and weather conditions beyond the range of experimental conditions, and the performance of the models developed in this thesis, needs to be evaluated. Careful documentation of wildfires is a useful technique for achieving this (e.g., see Alexander and Lanoville 1987).

Fine round twigs < 6 mm in diameter are the most flammable component of the jarrah forest litter bed. Fresh eucalypt leaves have a combustion rate equivalent to a 4 mm diameter round twig. While all dry fuel on the forest floor makes a contribution to flaming combustion, the upper size limit of fuels which contribute most to flaming zone combustion should be standardised at 6 mm in diameter. Combustion of material behind the flaming zone will influence the time/temperature signature of a fire, therefore its biophysical impact, so the size, quantity and distribution of other surface fuel particles consumed should be measured when studying fire effects.

Laboratory fire behaviour studies have limitations when attempting to model fire behaviour. It was not possible to accurately reconstruct the physical and chemical properties of actual litter beds in the laboratory. The small fires achievable in the laboratory do not display the same processes characteristic of large, intense fires in the field. Therefore, extrapolation from laboratory based experiments can be risky. The model developed from laboratory fires was found to be a linear function in wind speed and under-predicted the rate of spread of experimental field fires. This was probably due to scale limitations imposed by the laboratory which prevented fires from reaching a steady state rate of spread, especially at higher wind speeds. The relationship between rate of spread and slope determined in the laboratory was similar to that reported by other studies and was within the domain of that observed in the field. Examining the interaction of slope and wind in the field is likely to be impractical due to an inability to control factors such as wind speed and direction.

Byram's fire intensity and flame size are meaningful measures of scorch height. Byram's (1959) relationship between fire intensity and flame height and Van Wagner's (1973) relationship between fire intensity and scorch height did not hold for jarrah forest fuels. The relationships developed by this study have the same form as reported by these authors, but different coefficients, suggesting that flame structure and heat energy output varies between fuel types.

Heat load (area beneath thermocouple temperature history traces) and maximum temperature measured at the cambium of bull banksia stem sections was a strongly related to the quantity of fuel burnt by all phases of combustion and to bark thickness, but was weakly related to intensity and was independent of rate of spread. The quantity of fuel burnt reflects the amount of heat energy released, whereas bark thickness affects the amount and rate of heat transfer to the cambium. Therefore, using fire to reduce the abundance of plants such as bull banksia, a host to the fungal pathogen *Phytophthora cinnamomi*, can best be achieved by allowing fuels to accumulate and then burning under stable but dry conditions to ensure maximum fuel consumption. Such fires will also kill or damage small trees of commercial value and other non-target species. Tree damage resulting from the combustion of surface fuels and the associated chimney effect on the leeward side of stems, was a function of fire intensity and bark thickness. Fire intensities in excess of about 4,500 kW m^{-1} are likely to damage the stems of large, mature jarrah trees. The importance of fuel quantity, bark thickness and fire intensity on determining the extent of stem death or damage emphasises the need to maintain fuel quantities at low levels, particularly in regenerating forests where trees are small and have relatively thin bark.

Maximum soil temperature and heat load at a specific soil depth was best described by a linear function of the quantity of fuel consumed down to mineral earth, the moisture content of the soil and the moisture content of the fuel. Soil heating was weakly related to Byram's fire intensity but was independent of rate of spread. The Soil Heating Index (SHI) developed by this thesis is a numerical method of characterising the biological impact of a fire on top soil organisms. Jarrah forest fires burning in heavy fuels in summer or autumn when fuel and soil are dry, will have greatest impact on soil organisms such as hard seeds. The massive legume germination response often observed following summer wildfires is not related to fire intensity, but is due to the dry conditions of fuel, complete fuel consumption down to mineral earth, and to dry soil.

The experimentally-derived fire behaviour and impact models described in this thesis will perform best over the range of conditions under which they were derived. While there will be considerable variation in the field about mean predictions, these models and associated error statistics will allow jarrah forest managers, for the first time, to place confidence limits on all predictions. These models apply to a broader range of potential burning conditions than any previous models and should serve the current and foreseeable fire management of the jarrah forest.

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APPENDIX 1

List of symbols, variable descriptions and units.
This list closely follows standards proposed by Alexander (1982)
for forest fire descriptors.

Symbol	Variable	Units
r_F	rate of spread (headfire)	m h^{-1}
r_B	rate of spread (backfire)	m h^{-1}
h_F	flame height	m
L	flame length	m
D	flame depth	m
A	flame angle	degrees
F_S	flame shadow	m
L/W	Fire length-to-width ratio	
t	time	s, min., years
t_P	fuel bed pre-heat time	s
t_R	flame residence time	s or min
t_S	smoulder time	s or min
t_B	burn-out time	s or min
H	fuel heat yield	kJ kg^{-1}
I	Byram's fire intensity	kW m^{-1}
C	Combustion rate	kW m^{-2}
odw	oven dry weight	g or kg
w_C	fine fuel quantity (< 6 mm) consumed	t ha^{-1}
d	fuel particle diameter	mm
w_t	total fine fuel quantity (< 6 mm)	t ha^{-1}
F_S	available scrub fuel	t ha^{-1}
f_D	fuel bed depth	mm or m
f_B	fuel bed bulk density	kg m^{-3}
w_R	fuel residue quantity	t ha^{-1}
c_R	fuel consumption rate = w_C/t	kg min^{-1} m^{-2}
W_L	fuel rate of weight loss	g s^{-1}
MC	fuel moisture content	% of odw
SMC	MC of top 10 mm of fine litter fuel	% of odw
PMC	MC of entire profile of litter fuel	% of odw
LMC	MC of live vegetation	% of odw
AMC	MC of dead fine aerated (trash) fuel	% of odw
M_s	MC of soil	% of odw
S	slope	degrees
T_{10}	Thermocouple temperature at 10 cm	^oC
T_{MAX}	Maximum thermocouple temperature	^oC
T_{AS}	Ambient soil temperature	^oC
T_B	Temperature at bark surface	^oC
T_C	Temperature at cambium	^oC
S_h	Canopy scorch height	m
T_0	Soil surface temperature	^oC
T_5	Soil temperature at 5 mm	^oC
T_{10}	Soil temperature at 10 mm	^oC
T_{15}	Soil temperature at 15 mm	^oC
r_T	Response time (time to reach max. temp.)	s
H_L	Heat load (area beneath temperature trace)	degree mins.
U_L	Wind speed at 20 cm above the fuel bed	km h^{-1}
U	Wind speed at 2 m above forest floor	km h^{-1}
U_H	Wind speed at 10 m above forest floor	km h^{-1}
U_S	Wind speed at standard exposure	km h^{-1}
T_A	ambient air temperature	^oC
RH	relative humidity	per cent

APPENDIX 2

ANOVA tables for major predictive equations

Chapter 5

Equation 5-2: $W_t = 15.60(1-e^{-0.16t})$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	2	8175.6	4087.8	
Residual	47	410.6	8.7	15.60 (0.76)
Total (U/c)	49	8586.2		-0.16 (0.03)

Equation 5-3: $W_t = 8.10(1-e^{-0.18t})$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	2	1904.0	952.0	
Residual	44	380.6	8.6	8.10 (0.65)
Total	46	2284.6		-0.18 (0.053)

Equation 5-6: $F_S = 0.517t(e^{t*-0.072}$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	2	349.4	81.2	
Residual	94	81.2	0.86	0.517 (0.044)
Total (U/C)	96	430.6		-0.072 (0.005)

Chapter 6

Equation 6-1: $t_r = 0.871d^{1.}$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	2	138742.2	69371.1	
Residual	86	1472.6	17.1	0.871 (0.08)
Total (U/C)	88	140214.8		1.875 (0.03)

Equation 6-2: $t_r = 880.58S_{AV}^{-1.875}$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	2	138742.2	69371.1	
Residual	86	1472.6	17.1	880.58 (43.6)
Total (U/C)	88	140214.8		-1.875 (0.038)

Equation 6-3: $W_L = 36.98d^{-0.910}$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	2	1043.0	521.4	
Residual	37	67.8	1.8	36.983 (4.61)
Total (U/C)	39	1110.8		-0.910 (0.07)

Chapter 7

Equation 7-1: $r_F = (0.0245U^{2.22}+0.071)*(1/0.003+0.000922MC)$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	4	624356.5	156089.1	0.0245 (0.007)
Residual	56	11948.5	213.3	2.22 (0.142)
Total (Corr.)	59		636305.0	0.071 (0.050)

0.000922 (0.00029)

Equation 7-2: $h_F = 0.0013r_F + 0.032w_C$

Source	DF	Sum of Squares	Mean Square	Goodness of Fit
Regression	2	5.39	2.69	
Error	57	0.073	0.012	
Total	60	6.13		$R^2 = 0.88$

Equation 7-3: $L = 0.0024r_F + 0.036w_C$

Source	DF	Sum of Squares	Mean Square	Goodness of Fit
Regression	2	9.85	4.92	
Error	58	1.08	0.018	
Total	60	10.94		(No intercept fit)

Equation 7-4: $D = 0.0046r_F + 0.0047w_C$

Source	DF	Sum of Squares	Mean Square	Goodness of Fit
Regression	2	12.66	6.34	
Error	58	2.14	0.036	
Total	60	14.83		(No intercept fit)

Equation 7-5: $A = -5.08U + 2.01W_c + 77.4$

Source	DF	Sum of Squares	Mean Square	Goodness of Fit
Regression	2	9086.4	4543.2	
Error	57	1811.3	31.7	
Total	59	10897.7		$R^2 = 0.83$

Equation 7-6: $A = -0.13r_F + 2.18w_C + 66.5$

Source	DF	Sum of Squares	Mean Square	Goodness of Fit
Regression	2	8117.1	4058.6	
Error	57	2780.4	48.7	
Total	59	10897.6		$R^2 = 0.74$

Equation 7-7: $I = 912.8L^{1.373}$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	2	7147809.6	3573904.8	
Residual	58	794545.8	13699.0	912.8 (49.2)
Total (Corr.)	59	7942355.4		1.373 (0.097)

Equation 7-8: $I = 265.1L^{1.745}$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	2	498810.6	249405.3	
Residual	58	65012.0	1120.9	265.1 (14.1)
Total (Corr.)	59	563822.6		1.745 (0.12)

Equation 7-9: $r_F = 12.36*e^{(0.0687*S)}$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	2	17077.9	8538.9	
Residual	38	166.0	4.3	12.36 (0.44)
Total (U/C)	40	17243.9		0.0687 (0.003)

Equation 7-10: $L/W = 1.0 + 0.0236U^{2.114}$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	2	45.9	22.9	
Residual	14	0.3	0.02	0.0236 (0.01)
Total (U/C)	16	46.2		2.114 (0.24)

Chapter 8

Equation 8-1: $r_F = 23.192SMC^{-1.495} * U^{2.674} + 11.60$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	4	5861205.07	1465301.4	23.19 (4.03)
Residual	202	201653.92	849.0	-1.495 (0.04)
Total (U/C)	206	6032712.99		2.674 (0.09)
Total (C)	205	3335664.25		11.60 (4.37)

Equation 8-2: $h_F = 0.062r_F^{0.687}$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	2	651.18	325.60	
Residual	184	40.20	0.21	0.062 (0.007)
Total (U/C)	186	691.30		0.687 (0.22)
Total (C)	185	267.40		

Equation 8-3: $h_F = 0.00335r_F^{0.8259} * w_C$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	2	669.33	334.66	
Residual	184	28.68	0.15	
Total (U/C)	186	698.02		0.00335 (0.00036)
Total (C)	185	267.43		0.8259 (0.019)

Equation 8-5: $L = 0.0147I^{0.0767}$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	2	1072.6	536.3	0.0147 (0.0024)
Residual	183	54.1	0.29	0.0767 (0.023)
Total (U/C)	185	1126.8		
Total (C)	184	443.6		

Equation 8-6: $I = 293.8L^{1.118}$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	2	135402772.7	67701386.3	293.8 (14.6)
Residual	183	9232926.4	50453.1	
Total (U/C)	185	144635699.2		
Total (C)	184	72532683.6		

Chapter 10

Equation 10-1: $S_h = 1.49\{(0.742I^{7/6})/(60-T_A)[0.0256I+0.028U^3]^{1/2}\}+1.06$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Model	1	4309.5	4309.5	1.49 (0.07)
Error	183	2264.6	12.3	1.06 (0.43)
Total (C)	184	6574.2		

Equation 10-2: $S_{hS} = 4.92h_F+0.49$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Model	1	73.2	73.2	4.92 (0.59)
Error	48	51.3	1.0	0.49 (0.06)
Total (C)	49	124.5		

Equation 10-3: $S_{hA} = 8.53(h_F)+2.03$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Model	1	3119.1	299.3	8.53 (0.49)
Error	113	1177.3	10.4	2.03 (0.55)
Total (C)	114	4296.4		

Equation 10-4: $S_{hA} = 5.87L+2.82$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Model	1	3538.2	3538.2	5.87 (0.33)
Error	123	1412.1	11.4	
Total (C)	124	4950.4		

Equation 10-5: $S_{hA} = 0.28I^{0.579}$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	2	949.7	474.8	0.28 (0.09)
Residual	68	154.6	2.2	0.579 (0.06)
Total (U/C)	70	1104.4		
Total (C)	69	309.4		

Chapter 11

Equation 11-1: $T_{MAX} = 295.31\text{Ratio}^{-0.635}$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	2	15659583.2	7829791.6	
Residual	56	1000422.7	17864.6	295.3 (24.5)
Total (U/C)	58	16660005.9		-0.635 (0.06)

Equation 11-5: $T_C = 2.96w_C-5.16DOB+56.4$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	2	3916.8	1958.4	2.96 (0.81)
Error	31	4111.6	132.6	-5.16 (1.0)
Total	33	8028.4		56.4 (6.7)

Equation 11-6: $T_C = 2.35w_C-3.05BT+57.4$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	2	3938.7	1969.3	2.35 (0.78)
Error	31	4089.7	131.9	3.05 (0.59)
Total	33	8028.4		57.4 (6.8)

Chapter 12

Equation 12-1: $T_{DX} = (219.6/(DX+0.6))+4.16(w_C)-0.87(MC)-3.05(M_s)+5.6$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	5	8023778.1	2604755.6	0.62 (0.03)
Residual	203	468570.9	2308.2	4.16 (0.73)
Total (U/C)	208	8492349.0		-0.87 (1.0)
Total (C)	207	4782921.6		-3.05 (0.69)
				5.63 (12.8)

Equation 12-2: $SHI = 1.80(w_C)-1.61(MC)-1.30(M_s)+51.3$

Source	DF	Sum of Squares	Mean Square	Parameters (S.E.)
Regression	3	7307.5	2435.8	1.80 (0.23)
Error	52	4020.8	77.3	-1.61 (0.36)
Total	55	11328.4		-1.30 (0.21)
				51.3 (4.4)

APPENDIX 3

Equations used to predict rate of spread of fires in jarrah forest litter fuels using Rothermel's (1972) model.

W_o = litter quantity (t ha^{-1})*0.02048....convert to lb. ft.$^{-2}$
D = litter depth (mm)*0.00328.....convert fuel depth to ft.
SA = 2194..... fuel particle surface are-to-volume (ft.$^{-1}$)
H = 7996..... fuel particle low heat content (B.t.u. lb.$^{-1}$)
P_d = 34.3..... particle density (lb. ft.$^{-3}$)
M_f = moisture content (%)*0.01
S_T = 0.0555..... fuel total mineral content
S_e = 0.01...... fuel effective mineral content
U = wind speed (km h^{-1})*54.68.....convert wind to ft. min.$^{-1}$
S_L = 0.....slope
M_x = 0.21.....moisture content of extinction
P_R = 0.080....packing ratio
Q_{ig} = 250+(1 116*M_f)....heat of preignition (B.t.u. lb.$^{-1}$)
E_h = 2.71828**(-138/SA).... effective heating number
F_b = W_o/D.... oven dry bulk density (lb. ft.$^{-3}$)
SF = 0......slope factor
W_n = W_o/(1+S_T)...net fuel loading (lb. ft.$^{-2}$)
E = 0.175*(2.71828**(-3.59*0.0001*SA))
B = 0.02526*(SA**0.54)
C = 7.47*(2.71828**(-0.133*SA**0.55))
B_{op} = 3.348*(SA**-0.8189)....optimum packing ratio
W_c = (C*(U**B))*((P_R/B_{op})**-E)....wind coefficient
P_F = ((192+0.259*SA)**-1)*2.72**((0.792+0.681*SA**0.5)*(P_R+0.1)) propagating flux ratio
N_S = 0.174*S_e**-0.19....mineral dampening coefficient
N_M = 1-2.59*(M_f/M_x)+5.11*((M_f/M_x)**2)-3.52*((M_f/M_x)**3) moisture dampening coefficient
A = 1/(4.774*(SA**0.1)-7.27)
R_{max} = SA**1.5*((495+0.0594*SA**1.5)**-1)...maximum reaction velocity (min.$^{-1}$)
R_{opt} = R_{max}*((P_R/B_{op})**A)*2.71828**(A*(1-P_R/B_{op}))...optimum reaction velocity (min.$^{-1}$)
I_R = R_{opt}*W_n*H*N_M*N_S....reaction intensity (ft. min. $^{-1}$)
ROS = 18.288*((I_R*P_F*(1+W_c))/(F_b*E_h*Q_{ig}))...rate of spread (m h^{-1})