PREDICTING FIRE SPREAD IN WESTERN AUSTRALIAN MALLEE-HEATH SHRUBLAND

William Lachlan McCaw

Thesis submitted to the

School of Mathematics and Statistics

University CollegeUniversity of New South WalesCanberra ACT 2600 Australia

for the degree of
Doctor of Philosophy

December 1997

Certificate of Originality

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of a university or other institute of higher learning, except where due acknowledgement is made in the text.

William Lachlan McCaw
Manjimup 6258
Western Australia

31 December 1997

Acknowledgements

I am indebted to the various individuals and organisations who have assisted me to undertake post-graduate studies over the last seven years. These include:

- the Western Australian Department of Conservation and Land Management which provided the opportunity, rationale and resources for undertaking field-based fire behaviour research. In particular, I would like to acknowledge the enthusiastic support of Kelly Gillen, Terry Maher, Greg Broomhall and other staff of the South Coast Region who assisted with the experimental burning program at the Stirling Range National Park;

- Bob Smith and John Neal for their excellent technical assistance with fuel sampling, fuel moisture studies and experimental burning under field conditions that were often demanding;

- my supervisors Dr Ted Catchpole and Dr Wendy Catchpole of the School of Mathematics and Statistics at University College, and Dr Malcolm Gill of the CSIRO Division of Plant Industry at Black Mountain, Canberra. Their guidance, advice and hospitality is greatly appreciated. I also wish to thank Dr Colin Pask for supporting an external student whom he rarely saw, and Dr Martin Rayner for agreeing to represent CALM on my panel of supervisors;

- Dr David Weise of United States Forest Service, Dr Dick Williams of the CSIRO Division of Wildlife and Ecology, and an anonymous reviewer who made constructive comments which improved the final thesis;

- Joanne Elliot and Michelle Vellios for assistance with word-processing and formatting of this thesis,

- my wife Kerry and daughters Georgia and Darcie, both of whom arrived on the scene part way through these studies. They tolerated my prolonged absences at weekends and provided the support needed to see this project through to completion.

Abstract

Mallee-heath shrublands are an important and widespread vegetation type in south-western Australia. Despite the regular occurrence of large high intensity wildfires and the application of prescribed fire as a management tool in this vegetation type, fuel characteristics and fire behaviour in mallee-heath have recieved little attention to date. In this study, fuel characteristics, fuel moisture dynamics and fire behaviour were investigated in order to develop an understanding of the factors that control the spread and intensity of fires in mallee-heath.

Experimental work was conducted in a *Eucalyptus tetragona* mallee-heath community at the Stirling Range National Park. The mallee-heath community at the study site was floristically rich, and a large number of shrubs contributed to the fuel bed. Shrubs <1 m tall comprised more than half of the plant species recorded in sample quadrats and contributed the greater proportion of the plant cover and fuel loading. About 20 per cent of the vascular plants were fire sensitive shrubs with capsule-stored seed, some of which had primary juvenile periods of seven years or longer. Fuel accumulation was modelled as a function of time since fire, with the total fuel loading comprised of litter, dead fuel <25 mm and live fuel <6 mm remaining relatively constant after 10 years since fire. Total fuel loading in 20-year-old mallee-heath averaged 1.32 kg m^{-2}, of which about 1.15 kg m^{-2} was available fine fuel that would be consumed under moderate burning conditions. The proportion of total loading contributed by litter and dead fuel <6 mm continued to increase up to at least 20 years after fire, as did the cover of these components. Continued increase in the loading and cover of dead fine fuel is consistent with field observations that fires burn more readily in older stands of mallee-heath than in younger stands that have a comparable total fuel loading.

Diurnal variation in the moisture content of litter and elevated dead fuels was investigated over 11 days of sampling. Fuel moisture content varied substantially during the diurnal cycle in response to changing environmental conditions. During daytime conditions, litter fuel on the ground was consistently drier than elevated dead fuel suspended in shrubs. Observed moisture contents for litter and elevated dead fuel were compared with predictions from three empirical models commonly used in Australia, and a semi-physical formulation of equilibrium moisture content (EMC). Predictions from the EMC model were superior to those from the three empirical models for both litter and elevated dead fuel, regardless of whether fuel level temperatures were measured or calculated using an existing empirical relationship. Live foliage moisture content was sampled monthly between October 1991 and

September 1992 for two shrubs (*Dryandra drummondii* and *Lambertia inermis*) and a mallee eucalypt (*Eucalyptus pachyloma*) in order to obtain representative values for input to existing fire behaviour models, and to determine whether a seasonal pattern of variation in foliage moisture content existed. The moisture content of mature foliage from the three species remained between 70 and 100 per cent throughout the year. Mature foliage moisture content was not correlated with the Soil Dryness Index or the Keetch-Byram Drought Index.

Eighteen experimental fires were lit in 20-year-old mallee heath using 200 m line ignitions. Fires spanned a broad range of fire weather conditions with the most intense fires having forward rates of spread up to 0.67 m s^{-1} and frontal fire intensities up to 14 000 kW m^{-1}. The moisture content of the shallow litter layer beneath the low shrubs was found to have a controlling influence on fire spread, and fires spread freely when the moisture content of the shallow litter was below 8 per cent, regardless of wind speed. This threshold level of fuel dryness allowed fires to maintain a continuous front in the sparse fuels that occured beneath the layer of low shrubs. Forward rate of spread was modelled as a function of the wind speed in the open (U_2), and the moisture content of the deep litter beneath mallee clumps. The fitted model accounted for 84 per cent of variation in the rate of spread of experimental fires. Rate of spread predictions from the model matched well with observations from a limited number of prescribed and wild fires with rates of spread up to 1.1 ms^{-1}, although the observed spread rate of a wildfire burning under extreme fire danger conditions was about 30 per cent slower than predicted by the model.

Observed rates of spread of mallee-heath fires were compared with predictions from a range of existing fire spread models. Fires in mallee-heath spread faster than predicted for most other shrubland fuel types, with the exception of South African fynbos. The Rothermel fire model provided good rate of spread predictions when used in conjunction with a stylised fuel model for mallee-heath developed using the BEHAVE fire behaviour prediction system. Flame dimensions observed during experimental fires were compared with predictions from existing models. The fit of Byram's model for flame length was improved substantially by making a correction that accounted for flame extension due to combustion of the canopy layer. Flame heights predicted for buttongrass moorland were also similar to those in mallee-heath.

The investigations described in this thesis provide the framework for a system to predict the forward rate of spread, fireline intensity and flame length of fires burning in mature mallee-heath fuels. These fire behaviour attributes can be predicted from screen

level weather conditions and surface winds which are readily measured in the field. Prediction limits for fire spread are provided.

TABLE OF CONTENTS

Abstract iv

Chapter 1. Introduction

1.1 Fire management issues in south-western Australian shrublands 1
1.2 Thesis objectives and structure 7

Chapter 2. Vegetation and Fuel Characteristics of Mallee-Heath

2.1 Introduction 10
2.2 Quantifying fuels for fire behaviour prediction 11
2.3 The study area
2.3.1 Location and climate 16
2.3.2 Landforms, soils and vegetation 18
2.3.3 Layout of experimental plots 19
2.4 Methods
2.4.1 Floristic composition and structure of the vegetation 19
2.4.2 Assessment of fuel characteristics prior to experimental fires 22
2.4.3 Changes in fuel characteristics with increasing time since fire 24
2.4.4 Data analysis 25
2.5 Results
2.5.1 Vegetation structure and floristic composition 26
2.5.2 Fuel characteristics prior to experimental fires 35
2.5.3 Changes in fuel characteristics with increasing time since fire 50
2.6 Discussion 54
2.7 Conclusions 60

Chapter 3. Moisture Content of Dead and Live Fuels in Mallee-heath
3.1 Introduction 61
3.2 Dead fine fuels
3.2.1 Experimental methods 63
3.2.2 Models used to predict dead fuel moisture content 66
3.2.3 Data analysis 69
3.2.4 Results 71
3.2.5 Discussion 84
3.2.6 Conclusions regarding dead fuel moisture content 87
3.3 Live fine fuels
3.3.1 Factors affecting the moisture content of live fine fuel 88

3.3.2 Experimental methods 90
3.3.3 Results 91
3.3.4 Discussion 97
3.3.5 Conclusions regarding live fuel moisture content 100

Chapter 4. Experimental Studies of Fire Behaviour in Mallee-heath
4.1 Introduction 101
4.2 Fire behaviour models for shrublands 101
4.3 Experimental methods
4.3.1 Experimental site 105
4.3.2 Weather 106
4.3.3 Measurement of fuel moisture content 107
4.3.4 Calculation of drought and fire danger indices 108
4.3.5 Measurement of fire spread 108
4.3.6 Conduct of experimental fires 109
4.3.7 Estimation of flame dimensions 110
4.3.8 Estimation of fuel consumption 111
4.4 Data analysis 4.4.1 Weather data
113 4.4.2 Analysis of fire spread using data from electronic
timers 113 4.4.3 Statistical analysis
116 **4.5 Results** 4.5.1 Burning conditions for experimental fires
116
4.5.2 Development and spread of experimental fires 120
4.5.3 Factors critical to the initiation of fire spread 123
4.5.4 Comparison of forward rate of spread derived using contouring and triangulation methods 126
4.5.5 Variation in rate of spread, *R*, with time since ignition 131
4.5.6 Relationships between weather, fuel moisture content and *R* 134
4.5.7 Effect of wind speed on *R* 135
4.5.8 Effect of fuel moisture content on *R* 137
4.5.9 Effect of other environmental and fuel variables on *R* 141
4.5.10 Flame dimensions 142
4.5.11 Spotting and fire spread across areas devoid of fuel 144
4.5.12 Fuel consumption 148
4.5.13 Calculation of frontal fire intensity 160
4.6 Validation of the mallee-heath fire spread model against independent observations 160
4.7 Discussion

4.7.1 Threshold conditions for fires to sustain in mallee-heath 162
4.7.2 Factors affecting rate of spread in mallee-heath 165
4.8 Conclusions 169

Chapter 5. Comparison of fire behaviour in mallee-heath with fire danger indices and predictions from fire behaviour models

5.1 Introduction 170
5.2 Evaluation procedure
5.2.1 Rate of spread 172
5.2.2 Flame dimensions 178
5.3 Comparison of predicted and observed fire behaviour
5.3.1 Fire danger rating systems 179
5.3.2 Fire spread models 184
5.3.3 Flame dimensions 191
5.4 Discussion 195
5.5 Conclusions 198
Chapter 6. General Conclusions 200

References 205

Appendix A. Floristic data for mallee-heath 224

Appendix B. Glossary of commonly used symbols and abbreviations 228

Appendix C. Wind speed profiles in mallee-heath vegetation 229

Appendix D. Report on observations of wildfire behaviour in mallee-heath at the Fitzgerald River National Park 235

CHAPTER 1

INTRODUCTION

1.1 Fire management issues in south-western Australian shrublands

Plant communities dominated by woody shrubs occur in mediterranean environments on five continents, occupying significant areas in countries bordering the Mediterranean Sea and in southern Africa, the south-western United States, central Chile and southern Australia. Shrublands in mediterranean environments are characteristically fire-prone due to the annual occurrence of hot, dry weather during the summer months, and the sclerophyllous nature of the vegetation (Chandler *et al.* 1983). Fire has played a crucial role in fashioning mediterranean landscapes and remains one of the principal issues for land managers in these regions today (Mooney and Conrad 1977).

Shrublands are an important and widespread vegetation type in south-western Australia. Shrublands occur predominantly on the gently undulating sandplain landforms which extend from Kalbarri (27°43 S, 114°10'E) in the north to Israelite Bay (33°37'S, 123°53'E) in the south-east and up to 200 km inland (Beard 1984, Figure 1.1). These sandplain plant communities are known by the generic term kwongan (Beard and Pate 1984), which has a similar usage to the terms fynbos in South Africa, maquis in France and matoral in Chile. Kwongan communites are characterised by a stratum of shrubs up to 1 m tall, sometimes with a taller stratum of emergent shrubs or scattered trees. Generalised structural forms of kwongan have been defined on broadscale vegetation maps at scales ranging from 1: 250 000 to 1: 3 000 000 (Beard 1984). Despite having being extensively cleared for agriculture, kwongan shrublands still occupy an area of 5.5 million hectares within south-western Australia (Beard 1984).

On the sandplains that extend between Albany and Israelite Bay the most widespread form of kwongan shrubland is mallee-heath, which covers an area of about 550 000 ha. Mallee is a generic term used to describe short, multi-stemmed eucalypts which frequently have a gnarled growth habit. Mallee eucalypts are a characteristic feature of the vegetation throughout extensive areas of semi-arid Australia (Martin 1989). Typically, mallee-heath comprises a stratum of mallee eucalypts ranging in height from 3-5 m and cover from 20-50 per cent, above a shorter stratum of woody shrubs of variable density (Plate 1). Grasses are not generally an important component of the ground cover in mallee-heath communities on the southern sandplain, except in the first spring following fire when there may be a flush of ephemeral grasses such as *Stipa*. However, elsewhere in Western Australia and in semi-arid ares of south-eastern Australia mallee communities commonly have an understorey dominated by hummock grasses (Bradstock 1989). The flora associated with mallee-heath communities in Western Australia is very rich (Lamont *et al.* 1984), but classification and mapping of mallee vegetation in the State has generally been based on structural features of the vegetation and on the presence of particular species of eucalypts rather than on overall floristic composition. Mallee-heath is represented by the Open Scrub category in Specht's (1970) classification of the structural forms of Australian vegetation.

Much of the mallee-heath on the southern sandplain is reserved in national parks and nature reserves which are managed primarily for nature conservation purposes. These reserves are administered by the Western Australian Department of Conservation and Land Management (CALM). Mallee-heath vegetation is also widespread on areas of vacant Crown Land adjoining reserves managed by CALM. Reserves which contain extensive tracts of mallee-heath vegetation include the Stirling Range National Park, Fitzgerald River National Park, Cape Arid National Park and the Lake Magenta Nature Reserve. Although large in size (90 000-350 000 ha), these reserves are remnants of native vegetation within a landscape dramatically altered by clearing for agriculture. The majority of this clearing took place between 1950 and 1975.

Like most of southern Western Australia the southern sandplain is prone to periodic fires. Severe fire weather conditions characterised by extreme high temperatures, low humidity and strong winds occur regularly during the dry summer months, particularly in association with the formation of pre-frontal low pressure troughs along the west coast of the continent (Hanstrum *et al.* 1990). Easterly movement of these troughs is commonly accompanied by dry lightning storms that have the potential to ignite bushfires over a widespread area. Air photographs spanning the period since 1950 consistently show evidence of extensive fires, even in areas remote from land clearing and other sources of human-caused ignition (McCaw, unpubl. data). Extensive fires caused by lightning have occurred in Cape Arid National Park in 1983, in the Fitzgerald River National Park in 1985 and 1989 (McCaw *et al*. 1992), and in the Stirling Range National Park in 1996 and 1997 (Herford *et al*. 1996). In addition, some 750 000 ha of mallee and semi-arid woodland in remote areas of the south coastal hinterland burnt during a three month period in the summer of 1990/91 before being extinguished by rain (McCaw 1992). A characteristic feature of all these fire events has been the occurrence of major fire runs during periods of severe weather conditions.

During the past 50 years escaped land clearing burns have also been a significant cause of unplanned fires on the southern sandplain (Crook and Burbidge 1982) but these are becoming less frequent as clearing has now all but ceased in most districts. Other causes of unplanned fire include accidents involving vehicles and farm machinery and, occasionally, arson.

Fire is a critical issue for the management of both developed agricultural land and uncleared native vegetation on the southern sandplain. Fragmentation of the landscape has altered historical patterns and regimes of fire to the extent where it is no longer appropriate to allow the timing and extent of fires to be determined by chance ignition events. Because of the need to protect life, property and community assets from damage by wildfire, fires can no longer be allowed to start and spread at random in bushland areas adjacent to developed agricultural lands or in areas which receive high public usage or have developed facilities. Management of fire in remnant reserves must also take into account the fact that populations of fauna which rely on re-colonisation from adjacent unburnt bushland following disturbance may experience a serious decline if an entire remnant is burnt at the one time. Even small patches of unburnt vegetation within the perimeter of a large fire can provide important refuges for reptiles, birds and small mammals (Chapman and Newbey 1994). Within areas of native vegetation managed primarily for nature conservation, fire regimes also need to be compatible with conservation objectives, and with the requirements of species and communities that may be vulnerable to particular disturbance regimes (Hobbs 1987, Wardell-Johnson *et al.* 1989). In some cases fire may need to be temporarily excluded from an area, while in other cases prescribed fire may be an appropriate tool to regenerate plant communities (McCaw and Gillen 1993).

Organised fire management in bushland areas along the south coast of Western Australia is a relatively recent development. Until the mid 1970's, most of the parks and reserves had no permanent management staff, and were either totally unmanaged or subject only to limited intervention by local residents. Such intervention generally took the form of burning-off during during the late autumn to create fuel-reduced zones around property assets, and back-burning from agricultural lands in the event of wildfire. Fire management strategies have evolved rapidly in the past decade in response to improved resource information, establishment of formalised planning procedures for CALM lands, changing community expectations, and growing experience on the part of land managers (Burrows *et al*. 1989).

Figure 1.1 South-western Australia, showing the original extent of mallee-heath shrublands prior to agricultural development (after Beard 1984) and place names mentioned in the text.

Plate 1 A view of the landscape on the southern side of the Stirling Range with evidence of a recent extensive fire in mallee-heath.

Plate 2 An intense fire developing in mature mallee-heath vegetation under dry summer conditions with a 10 m open wind speed of 4.4 m s^{-1}. Photograph taken of Plot G at the Stirling Range experimental site.

Important factors that affect the conduct of fire management operations in bushland reserves on the southern sandplain include remoteness, limited vehicle access, scarcity of surface water, and the restricted availability of funds and personnel to undertake operations in the field. Prior to 1985 the most common fire management strategy for large reserves was to undertake limited fuel reduction burning within narrow buffer strips (100-500 m wide) located at the interface between the reserve and neighbouring lands of different tenure. In practice, mallee-heath vegetation has proved difficult to burn within the confines of narrow buffer strips because slight changes in fuel and weather conditions can lead to dramatic alteration in fire behaviour (McCaw *et al*. 1992). If burning conditions are too mild, fires do not sustain in mallee-heath and fuel reduction within buffer strips is ineffective. Unsuccessful attempts at prescribed burning are also wasteful of resources. Conversely, if fire behaviour is too severe, fires are likely to escape from buffer strips, posing a threat to neighbouring lands and potentially endangering personnel at the fireface. Extensive systems of perimeter buffers also result in ongoing maintenance costs, increased potential for soil erosion, and an increased risk of spreading soil-borne fungi of the genus *Phytophthora* which cause destructive plant disease in a range of shrubland communities (Wills 1992).

Within the last decade, fire managers have begun to investigate the feasibility of establishing networks of strategically-located fuel-reduced zones within large, unroaded blocks of native vegetation (McCaw and Gillen 1993, Herford *et al.* 1996). One method successfully employed to establish such zones has been to ignite fires during periods of strong, pre-frontal northerly winds during the cooler winter months when rising humidity or rain are likely to extinguish the fire overnight (Duxbury 1984). This approach is suited to larger and more remote reserves where the precise extent and location of the area burnt is not of great concern to managers. Since 1990 the use of aerial ignition to burn patches and strips in large blocks of mallee-heath has been found to have considerable promise. Aircraft provide flexibility in the pattern and intensity of lighting, and facilitate ignition in remote or otherwise inaccessible terrain. To date aerial ignition has mostly been undertaken within defined blocks where the perimeters have first been secured by scrub-rolling and burning strips of vegetation along existing access tracks. This has permitted aerial ignition to be undertaken during warmer and drier weather conditions, and with a broader range of wind directions than is generally possible where only rising humidity or rain are being relied upon to contain the fires to the prescribed size. In some situations fuel-reduced zones can be used to link areas naturally devoid of flammable vegetation, such as the extensive salt lakes which are common at the drier inland margins of mallee-heath range.

Regardless of whether prescribed burning is undertaken within narrow perimeter buffers or on a broadscale basis, managers need to be able to predict fire behaviour to ensure that prescribed fires meet stated objectives for area coverage, fuel consumption and intensity, and that fires do not escape beyond the defined boundaries of burning cells. Successful application of prescribed fire in mallee-heath depends to a large degree on being able to reliably predict the onset and cessation of fire spread. Fire behaviour predictions are also required for objective evaluation of wildfire threat (Muller 1993), and for planning effective suppression strategies for wildfires from damage by wildfire.

Fuel characteristics and fire behaviour in mallee-heath have recieved little attention to date, despite the regular occurrence of large high intensity fires in this vegetation type. Preliminary research into factors affecting fire spread in mallee-heath was undertaken in the Stirling Range National Park by officers of the Western Australian Forests Department in 1973-1974, and a number of small scale experimental fires were lit (Jones 1973, 1974). Unfortunately, this work was discontinued before the full program of experimental burning could be completed. Forward spread rates and other aspects of fire behaviour under severe weather conditions have been documented for several wildfires by McCaw *et al.* (1992), but such observations are not necessarily relevant to the application of prescribed fire as a management tool. Some fire behaviour research has been undertaken in mallee shrublands in semi-arid south-eastern Australia (Noble *et al.* 1980, Bradstock and Gill 1993) but this is not directly applicable to mallee-heath in western Australia because of important differences in composition and the structure of the fuel array.

1.2 Thesis objective and structure

This thesis presents the results of studies undertaken to develop an understanding of the factors that control the spread and intensity of fires in mallee-heath on the southern sandplains of Western Australia.

In order that the work have broad applicability, the experiments were undertaken in a mallee-heath community that is widespread on the southern sandplain. This community is characterised by the presence of *Eucalyptus tetragona*, and has been mapped at 1:250 000 scale (Beard 1984). These vegetation maps define, in the broad scale, the geographic range to which the results of this work may be applicable.

Important aspects of the development of a fire spread model for mallee-heath are described in the following five chapters of this thesis.

Chapter 2 describes the vegetation and fuel characteristics of a 20-year-old stand of *E. tetragona* mallee-heath at the Stirling Range National Park. Loading, compactness, particle size class distribution and spatial arrangement of the fuel bed are examined. The accumulation of fuel load and increase in plant cover with increasing time since fire are modelled. Reproductive characteristics of selected shrubs are examined as a basis for determining the effects of differing fire intervals on the structure and plant species composition of mallee-heath.

Chapter 3 investigates the diurnal variation in moisture content of several different components of the dead fine fuel in mallee-heath. A number of existing models that could be used to predict fuel moisture content are evaluated to determine whether they are suitable for use in mallee-heath. The extent of seasonal variation in the moisture content of live foliage from two common shrubs and a mallee eucalypt is examined in order to provide representative data for use in existing fire spread models for shrubland, and for comparison with shrubs from mediterranean environments elsewhere in the world.

Chapter 4 describes the behaviour of experimental fires in mallee-heath over a broad range of burning conditions. Environmental factors that are critical to the initiation and spread of fires are identified. The effects of various environmental and fuel variables on fire spread are examined, and a fire spread model based on wind speed and dead fuel moisture content is presented. Predictions from this model are compared with independent fire spread observations from prescribed and wildfires.

Chapter 5 compares observed rates of spread and flame dimensions of experimental fires with predictions from a number of existing fire spread models, some of which have been specifically developed for shrubland fuel types elsewhere. Possible reasons for differences between predicted and observed fire behaviour are discussed.

Chapter 6 draws general conclusions from the studies and identifies issues which, through further investigation, may lead to a better understanding of fire behaviour in mallee-heath and similar shrublands.

Some relevant data sets and sections of the analysis are appended separately, as follows:

> Appendix A contains a list of vascular plants recorded from fourteen 10 m x 10 m quadrats at the experimental site in the Stirling Range National Park. Details of cover and height class for each plant taxa are provided.
>
> Appendix B contains a list of symbols and abbreviations commonly used in the text.
>
> Appendix C describes an experimental investigation of the relationship between wind speed measured at 10 m height in the open and wind speed at various heights in mallee-heath. A function relating wind speed at 10 m and 2 m height in the open is also presented. These functions were used in the analysis of wind speed data from experimental fires, and can be used to convert wind speeds at the standard observation height of 10 m in the open to a 2 m equivalent, as required in the mallee-heath fire spread model.
>
> Appendix D is a previously published technical report (McCaw *et al*. 1992) which examines the behaviour of wildfires which burnt under extreme fire weather conditions in the Fitzgerald River National Park in December 1989. Rate of spread observations from these fires form part of the data set used to validate the experimentally-derived fire spread model for mallee-heath developed in this thesis.

CHAPTER 2

VEGETATION AND FUEL CHARACTERISTICS OF MALLEE-HEATH

2.1 Introduction

Fuel structure, loading and continuity play a major role in determining fire behaviour. The way in which fuels have been characterised has been determined to a large extent by the requirements of models that are used to predict fire behaviour. Some fire behaviour models require relatively simple measures of fuel condition such as the age of the vegetation since the last fire (Marsden-Smedley and Catchpole 1995a) or the loading of dead fine fuel (McArthur 1967 & 1977, Sneeuwjagt and Peet 1985) while others require a detailed description of height, loading, particle size distribution and fuel chemistry (Rothermel 1972, Burgan and Rothermel 1984). These differing requirements have, in turn, had a major influence on the development of techniques to describe and quantify fuels in the field. Little published information is available about fuel characteristics in Western Australian shrublands, and this section of the study addresses this deficiency by quantifying important physical characteristics of the fuel in a 20-year-old stand of mallee-heath at the Stirling Range National Park. Fuel characteristics examined include loading, particle size distribution, bulk density and the proportion of dead fuel. Some of these attributes are used as inputs to existing fire behaviour models. Appropriate input values are required to determine whether existing models are satisfactory for predicting fire behaviour in mallee-heath. The structure and floristic composition of the vegetation are also examined as a basis for comparison with shrublands elsewhere in Australia and overseas.

The time interval since fire affects both the loading and composition of the fuel, and the maturity of the plant community as a whole. A knowledge of the regenerative strategies employed by plants allows predictions to be made about how the structure, species composition and fuel characteristics of a community may change according to the frequency of fire (for example Gill 1981, Noble and Slatyer 1981, Van Wilgen 1981). Plant attributes also provide a useful guide to the minimum period between fires that is necessary to ensure that the floristic composition of the plant community is maintained in the long term (Benson 1985, Gill and McMahon 1986, Bradstock and Myerscough 1988, Witkowski *et al*. 1991, Bradstock *et al*. 1996). This study examines a sequence of mallee-heath stands ranging from one to 20 years since in order to determine the likely influence of vegetation age on fire behaviour. Structural characteristics examined include vegetation height and cover, fuel loading and the proportion of dead fuel. Post-fire regenerative strategies of common plant species occurring in mallee-heath at the Stirling Range are described, and the length of time to first flowering after fire is determined for a selection of species which rely on seed to re-establish after disturbance. Based on these plant attributes, an estimate is made of the inter-fire period necessary to ensure persistence of plant species within the mallee-heath community.

2.2 Quantifying fuels for fire behaviour prediction

The arrangement, amount and condition of the fuel through which a fire spreads exert a major influence on the resultant fire behaviour. Individual fuel particles of varying size, shape, orientation, moisture content and chemical composition are aggregated into fuel beds which can be described in terms of characteristic loading, depth and horizontal continuity (Brown and Davis 1973, Pyne 1984). Many vegetation types, including shrublands, consist of several distinct layers, or strata, separated by vertical discontinuities. Typically, these strata include a surface fuel layer of leaf litter and dead twigs on the ground, and a layer of near-surface fuel which may include grass, low shrubs and suspended dead leaves and bark. In some vegetation types, a stratum of taller shrubs and trees may also be present.

The feature which sets shrublands apart from many other fuel types is that the living vegetation itself comprises a substantial part of the available fuel. This contrasts with the situation in many forest types where the fuel consists predominantly of leaf litter and other dead plant material distributed in a layer on the forest floor. Likewise, fires are unlikely to spread in temperate grasslands until at least 60 per cent of the sward has died and undergone a curing process (Luke and McArthur 1978).

Description and measurement of fuel beds has generally been undertaken with the objective of providing the inputs necessary to predict fire behaviour using empirically or mathematically-derived models (McCaw 1991). In Australia, empirically-derived models have been developed to predict the behaviour of fires in grasslands (McArthur 1973, 1977) and open eucalypt forests (McArthur 1967, Sneeuwjagt and Peet 1985). These models apply to important, widespread vegetation types which are characterised by sets of generalised fuel parameters. The McArthur Forest Fire Danger Meter Mark V (FFDM) assumes that the loading and moisture content of fine dead fuel (<6 mm diameter) are the only fuel variables to have a significant influence on the behaviour of surface fires in dry sclerophyll open eucalypt forests, once the fine fuels are dry and available for combustion. The Forest Fire Behaviour Tables (FFBT) developed for jarrah (*Eucalyptus marginata*) and karri (*Eucalyptus diversicolor*) forests in Western Australia (Sneeuwjagt and Peet 1985) also allow for the contribution of understorey shrub foliage to fire behaviour, in addition to the loading and moisture content of fine dead fuel. Shrub fuels are accounted for using a scrub flammability factor which varies according to the proportion of dead foliage present and a subjectively-assigned foliage flammability rating. For grassland fuels, both the Mark IV and Mark V fire danger meters developed by McArthur (1973, 1977) take into account the effect of fine dead fuel moisture content and the extent of fuel curing on fire behaviour, but only the Mark V meter accounts for the effect of fine fuel loading.

These empirically-based fire spread models have been widely employed for fire danger rating and fire behaviour prediction, and are generally considered to perform adequately within the range of conditions for which they were developed. However, a comprehensive experimental study of fire behaviour in grasslands found no evidence of a relationship between fuel load and rate of spread in continuous swards of either coarse or fine grasses (Cheney *et al.* 1993). Differences in the rate of spread between fires in natural grass swards and in cut grass could also not be fully explained by changes in the height or bulk density of the fuel bed. Condon (1979) suggested that the Mark IV grassland meter required modification to account for variation in sward height and species composition in semi-arid pastures in the Western Division of New South Wales, while Griffin and Friedel (1984) found the Mark IV grassland meter unsuitable for use in discontinuous hummock grasslands in Central Australia.

The Canadian Forest Fire Behaviour Prediction System (Forestry Canada 1992) is also based largely on empirically-derived algorithms which link fire spread to the effects of fine fuel moisture content and wind speed. An Initial Spread Index incorporating these effects provides the basis for predicting fire danger and fire behaviour in 16 different fuel types. Fuel types are defined as identifiable associations of fuel elements having distinctive species composition, form, size, arrangement and other characteristics that will cause a predictable rate of fire spread or difficulty of control under specified burning conditions. These fuel types represent important vegetation associations for which generalised fuel characteristics have been described, and which are assumed to relatively homogeneous within the type.

An alternative approach to fire danger rating and fire behaviour prediction taken in the United States employs a physically-based fire spread model developed by Rothermel (1972). Variable fuel inputs to this model include fuel surface area to volume ratio, loading, depth, live to dead ratio, moisture content and extinction moisture content, by fuel particle size. Stylised fuel models representative of one or more important vegetation types have been constructed to make these more complex fuel descriptors accessible to practitioners (Albini 1976, Anderson 1982). For fuel types not represented by the stylised models, site specific fuel models may be constructed using the BEHAVE system (Burgan and Rothermel 1984).

Implicit in most current fire behaviour models are the assumptions that the fuel bed is uniform and continuous, and that fire spread takes place predominantly within a single fuel stratum, most often that comprising the surface litter and near-surface fuel. These assumptions are reasonable for fires in temperate grasslands and for low intensity surface fires in open forests that lack a well developed stratum of understorey shrubs or advance growth. However, the first of these assumptions is violated in vegetation types where the degree of horizontal discontinuity in the fuel bed is sufficient to prevent fires from spreading under certain weather conditions. This situation is exemplified by the hummock grasslands which are widespread in the arid zone of the Australian interior and consist of discrete hummocks separated by expanses of bare mineral soil (Griffin and Allan 1984, Burrows *et al*. 1990, Bradstock and Gill 1993, Gill *et al.* 1995). Furthermore, the assumption that fires spread within a single fuel bed is violated when fires extend vertically into a layer of tall shrubs or tree crowns, either by means of direct contact with flames from a surface fire or through combustion of so-called ladder fuels such as loose bark, resin or lichen (McCaw 1991, Wilson 1992). Factors associated with the initiation and spread of crown fires in conifer forests have been investigated to provide a basis for fire behaviour predictions (Van Wagner 1977, Rothermel 1991), and some progress has been made towards the development of a physical model for crown fires (Albini 1985 & 1986, Albini and Stocks 1986). Crown fires in vegetation types other than conifer forests have received little attention.

Shrublands exhibit a wide range of structural forms depending on the age and growth habit of the species comprising the stand, and on the degree to which the stand has been modified by disturbance such as past fires, grazing, plant disease and drought. Amongst the more homogeneous shrublands are even-aged monospecific stands which form a single stratum of relatively uniform height. Notable examples of relatively uniform shrublands include *Calluna vulgaris* heath from Great Britain (Kayll 1966, Thomas 1971, Hobbs and Gimingham 1984), and *Allocasuarina nana* heath from south-eastern Australia described by Catchpole (1985). Despite their apparent uniformity, the potential variability in fire behaviour in these heaths has been found to be considerable. Catchpole (1985) distinguished three separate strata within the *A. nana* fuel bed including a surface layer of dead litter, a middle layer of twigs and branches, some of which were dead, and an upper layer of live foliage. Each of these strata could potentially contribute in a different way to fire spread. Kwongan shrublands in the south-west of Western Australia are, in constrast to the above examples, highly heterogeneous and amongst the most species-rich plant communities described (Lamont *et al.* 1984). In species-rich shrublands, variability in species composition and vegetation structure may contribute to further localised variability in fire behaviour and the thermal environment (Hobbs and Atkins 1988), beyond that normally associated with important environmental influences such as wind, fuel moisture and slope. Species-linked characteristics which may influence fire behaviour include leaf shape and orientation, fuel moisture and volatile oil content of foliage, the proportion of dead foliage on the plant, and the nature of the litter layer accumulated beneath individual plants.

There has been only limited study of the factors that may affect fire spread in discontinuous fuels and control the transition from one type of fire to another. Van Wagner (1977) proposed that the critical fire intensity required to initiate crowning in dense conifer stands depends upon the extent of separation between the surface and crown fuel layers, and the foliar moisture content of the crown layer. These same factors, amongst others, are also likely to influence the propensity for fires to extend vertically to the shrub and tree strata in other vegetation types. A multi-stratum elaboration of the Rothermel model has been developed which assumes that a fire will spread through the stratum which permits maximum rate of spread (Bevins 1976, Kessell *et al*. 1978). This model was evaluated in two different south-eastern Australian shrublands by Catchpole (1987a, b) and found to give poor predictions of forward rate of spread.

Several different approaches have been proposed for determining fire spread characteristics in horizontally-discontinuous fuels. Gill *et al.* (1995) suggested that an initiation-of-spread analysis should be undertaken prior to predicting forward rate of spread in spinifex hummock grasslands. For fires to spread in this fuel type flames must be sufficiently long and winds sufficiently strong to tilt flames across to the next hummock for a period long enough to ignite it. An initiation-of-spread analysis would require that specific threshold conditions of gap width, wind strength, flame length, discrete hummock fuel loading and fuel moisture be satisfied before fire could spread.

Griffin and Allan (1984) also studied fires in spinifex hummock grasslands and found that a patchiness factor, defined by the variance/mean ratio of the size of hummocks and bare patches was useful in assessing the likelihood of fire spread under various sets of weather conditions. Fire spread models developed for hummock grasslands have identified the existence of threshold wind speeds required for fires to spread (McArthur 1972, Burrows *et al*. 1991, Griffin and Allan 1984, Gill *et al.* 1995); threshold wind speeds vary considerably and are presumably specific to particular fuel situations. Frandsen and Andrews (1979) proposed that the Rothermel model could be applied to heterogeneous fuels by visualising the fuel bed as a hexagonal grid comprised of individual cells within which the fuel characteristics are constant. Fire spread, and the ultimate shape of the fire front could then be modelled by integrating the predicted fire behaviour within individual cells. The situation of horizontally discontinuous fuels could be accommodated within this framework by assuming that some of the cells within the grid contained no fuel, although decisions rules would need to be developed to determine under what circumstances a fire might be able to cross a gap represented by an empty cell. For this approach to offer realistic predictions of fire spread the scale of the grid would need to reflect the scale of variability within the fuel bed.

In a given vegetation type, fuel characteristics vary according to the age of the stand. For shrublands occuring in fire-prone evironments, the age of the vegetation will normally correspond to the time elapsed since the last fire; patchy fires can, however, result in the formation of locally uneven-aged stands. Important age-linked fuel characteristics include height, loading, cover, and the proportion of dead foliage. Age-linked variation in species composition may also affect fuel characteristics in shrublands which experience a flush of ephemeral plants, particularly grasses, in the immediate post-fire environment (eg. Delfs *et al.* 1987). Hobbs and Gimmingham (1984) found that fire intensity was correlated with stand age in *C. vulgaris* heath, at least up to the late mature phase of stand development. Changes in fuel characteristics following fire have been examined in a range of Australian shrublands ranging from buttongrass moorlands in perhumid south-west Tasmania (Marsden-Smedley and Catchpole 1995a) to dry heath communities in South Australia (Specht 1966) and the Sydney region (Conroy 1993). In Western Australia, Burrows and McCaw (1989) developed a fuel accumulation curve for *Banksia* woodlands on the Swan Coastal Plain which showed that fine fuels reached an equilibrium loading of about 0.7 kg m^{-2} within 12 years after fire. Delfs *et al.* (1987) reported that cover and biomass in coastal heathland at Badgingarra, 200 km north of Perth, increased rapidly in the first seven years following fire, but remained relatively constant thereafter. Biomass was also measured in a mature shrubland at Tutanning Nature Reserve in the Western Australian wheatbelt by Brown and Hopkins (1983).

Similar studies of age-related change in plant community biomass and structure have been undertaken in many of the major shrubland communities from mediterranean climate regions of the world (Specht 1969, Rothermel and Philpot 1973, Kruger 1977, Van Wilgen 1982a, Paysen and Cohen 1990, Riggan *et al*. 1995).

Most investigations of fuel accumulation following fire have utilised comparable sites with different ages since fire, rather than repeated sampling at the one site. The utility of the former approach depends on the extent to which sites can be matched to minimise variation due to factors other than time since fire.

2.3 The study area

2.3.1 Location and climate of the experimental site

Experimental studies were undertaken in the Stirling Range National Park (34° 31'S, 118° 15'E), about 90 km north of Albany, in southern Western Australia (Figure 2.1). This region of Western Australia experiences a dry mediterranean climate with cool moist winters and warm dry summers (Beard 1984). However, because of the proximity of the Stirling Range to the coast and the orographic influence of the terrain, periods of moist, drizzly weather may occur at any time throughout the year (Courtney 1993). Mean daily maximum and minimum temperatures at Mount Barker, about 55 km south-west of the experimental site, are 27.2°C and 13.5°C in the hottest month (January) and 14.7°C and 6.4°C respectively in the coldest month (July) (Bureau of Meteorology data 1991). The nearest official rainfall recording station to the site is at Kojaneerup, about 10 km to the south-east, where the annual average rainfall is 472 mm. Average monthly rainfall exceeds 50 mm during the five months from May to September and is less than 25 mm during the three months from December to February (Figure 2.2). Occasionally, heavy rainfall occurs during the summer months in association with low pressure systems of tropical origin.

During the winter months the regular movement of low pressure systems and cold fronts along the south coast of Western Australia maintains a predominantly westerly air flow over the area (Courtney 1993). In summer, wind patterns are strongly influenced by the position and strength of a low pressure trough that regularly develops along the west coast of the continent. On the eastern side of the trough, north-easterly winds bring hot, dry air from the interior of the continent while on the western side of the trough conditions are moderated by cooler on-shore winds. Strong, afternoon sea breezes from the south-east occur regularly during the summer months, with wind speeds experienced on the southern side of the Stirling Range typically in the range 25-30 km/h. Although these on-shore breezes tend to moderate temperature and relative humidity extremes, fire danger is usually elevated by the onset of the sea breeze because of the increased wind speed. McCaw *et al*. (1992) examined the frequency of daily forecast fire danger ratings, based on the Mark IV Grassland meter, for the Western South Coast forecast District which includes the Stirling Range National Park. For six fire seasons spanning the period 1982/83 to 1989/90 the mean number of days forecast for the upper three categories of fire danger were: HIGH (79), VERY HIGH (20) and EXTREME (7). The weather pattern that most frequently results in EXTREME fire danger in this part of the State is the development of a pre-frontal trough (Hanstrum *et al.* 1990, Bannister and Hanstrum 1994). Ex-tropical cyclones can also create severe fire weather conditions over the south-west of the State, with an expected return period of about five years (Hanstrum 1989).

Figure 2.1 Location of the study area and the Stirling Range National Park in the Albany region of south-western Australia.

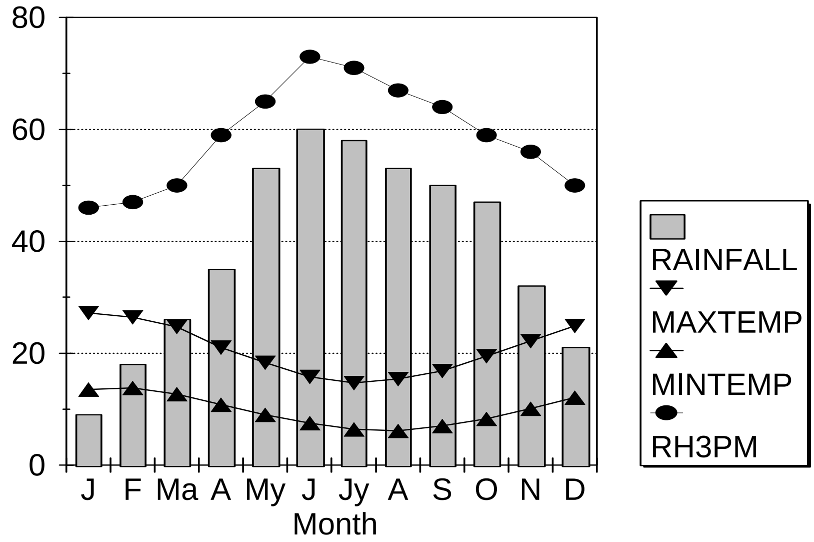


Figure 2.2 Climatic data representative of the Stirling Range study area, based on mean monthly rainfall (mm) at Kojaneerup, and mean daily maximum and minimum temperature (°C) and 3 pm. relative humidity (%) at Mount Barker. Source: Bureau of Meteorology, 1991.

2.3.2 Landform, Soils and Vegetation of the experimental site

The experimental site was located at an elevation of 160 m above sea level on a broad plain that extends southwards from the Stirling Range. The underlying rock in this area is Proterozoic gneiss of the Albany-Fraser Province, which is overtopped by Cainozoic sediments of the Bremer basin (Semenuik 1993). Soils at the experimental site consisted predominantly of brown sandy-gravels with lateritic pisoliths (small ironstone nodules), interspersed in a mosaic with sheets of white sand overlying laterite (Churchward *et al.* 1988).

The vegetation at the experimental site was mallee-heath, described as a *Eucalyptus tetragona* mallee-heath formation by Keighery and Beard (1993). At the commencement of the experiment the vegetation was 20 years old, having last been burnt in 1969 by an intense summer fire that consumed the shrub layer and crowns of the mallee eucalypts. The study area was chosen to provide as uniform an area of mature vegetation as could reasonably be achieved at the scale required for the proposed experimental burning program (100 ha approx.).

2.3.3 Layout of experimental plots

Prior to the construction of tracks and experimental plots, the site was surveyed to assess the likely distribution of the fungus *P. cinnamomi*. Two CALM officers experienced in the interpretation of symptoms associated with *P. cinnamomi* plant disease assessed the condition of the vegetation along sample lines located at 50 m intervals across the site, and recorded any deaths of plant species known to be susceptible to the fungus. Thirteen soil samples were collected and subsequently tested for the presence of *P. cinnamomi*. There was some evidence of *P. cinnamomi* impact at the site, and one soil sample collected from a small area of obviously disease-affected vegetation at the north-east corner of the site tested positive for *P. cinnamomi*. This area was subsequently avoided during plot construction and experimental burning operations in order to minimise the risk of spreading the fungus by moving infected soil. Over the remainder of the site a diverse range of potentially-susceptible plant species were observed to be apparently unaffected by disease.

A grid of sixteen 4 ha plots, each approximately 200 m x 200 m, was demarcated with a bulldozer in March 1989. Plots were grouped into cells of four, each cell being surrounded by a 100 m wide strip in which the vegetation was scrub-rolled with a length of heavy anchor chain towed between two bulldozers (Plate 3, Figure 2.3). Scrub-rolled strips were burnt in early April 1989 to establish fuel-reduced buffers that permitted experimental fires to be conducted under relatively severe burning conditions without undue risk of escape. Two larger plots (16 ha and 50 ha in area) established nearby in similar mallee-heath as part of a study of the response of fauna to fire were also burnt during the period of the experiment; relevant fire behaviour data from these plots have been used in some analyses. In July 1989, the study area was photographed vertically from a light aircraft using a Hasselblad 70 mm camera and colour film. Prints were enlarged to 1:2000 scale.

2.4 Methods

2.4.1. Floristic composition and structure of the vegetation

Prior to burning, the floristic composition and structure of the vegetation was described from fourteen 10 m x 10 m quadrats established in structurally uniform vegetation. Quadrats were located on a brown, sandy-gravel soil type and provided floristic data representative of the vegetation covering the majority of the experimental site, with the exception of areas on white sand substrates and in localised swampy depressions. The presence, cover, and height class of all vascular plants within each quadrat was initially assessed between October and December 1989. Cover was estimated visually using a cover abundance scale divided into the following categories: (1) plants rare, <1 per cent cover, (2) any number of plants with <1 per cent cover, (3) any number with 1-5 per cent cover, (4) any number with 5-10 per cent cover, (5) any number with 10-25 per cent cover. Each quadrat was re-visited on a further three occasions prior to burning (February, May and September 1990) to check for the presence of additional species not detected initially. Voucher specimens of all plants were collected, dried and mounted. The set of voucher specimens is registered with the Western Australian Herbarium. Specimens were identified using keys and with the assistance of Mr Tony Annels and Mr Ray Cranfield of the Department of Conservation and Land Management. Plant nomenclature follows Green (1985). A complete list of plants recorded in the quadrats is provided in Appendix A.

Plants were categorised according to their post-fire response using the classification proposed by Gill (1981). The primary division within this classification is made according to whether plants in the reproductive phase die or recover following complete crown scorch by fire. Subsequent divisions of the classification depend on the location of seed storage and regenerative buds on the plant. Plants which die following complete leaf scorch are referred to as fire sensitive. The period of time between fire and first flowering, commonly refered to as the primary juvenile period (Gill 1975), was determined for the subset of fire sensitive species that had seed stored in capsules or follicles on the mature plant. Plants which rely on on-plant seed storage for regeneration are vulnerable to elimination if the period between fires is shorter than the period required for re-establishment of an adequate store of seed. Such species are valuable as indicators of the frequency of fire that is compatible with plant species conservation (Gill and Nicholls 1989). Understanding the fire response strategies of plant species also makes it possible to predict how the floristic composition, structure and fuel characteristics of the vegetation may be affected by different fire frequencies.

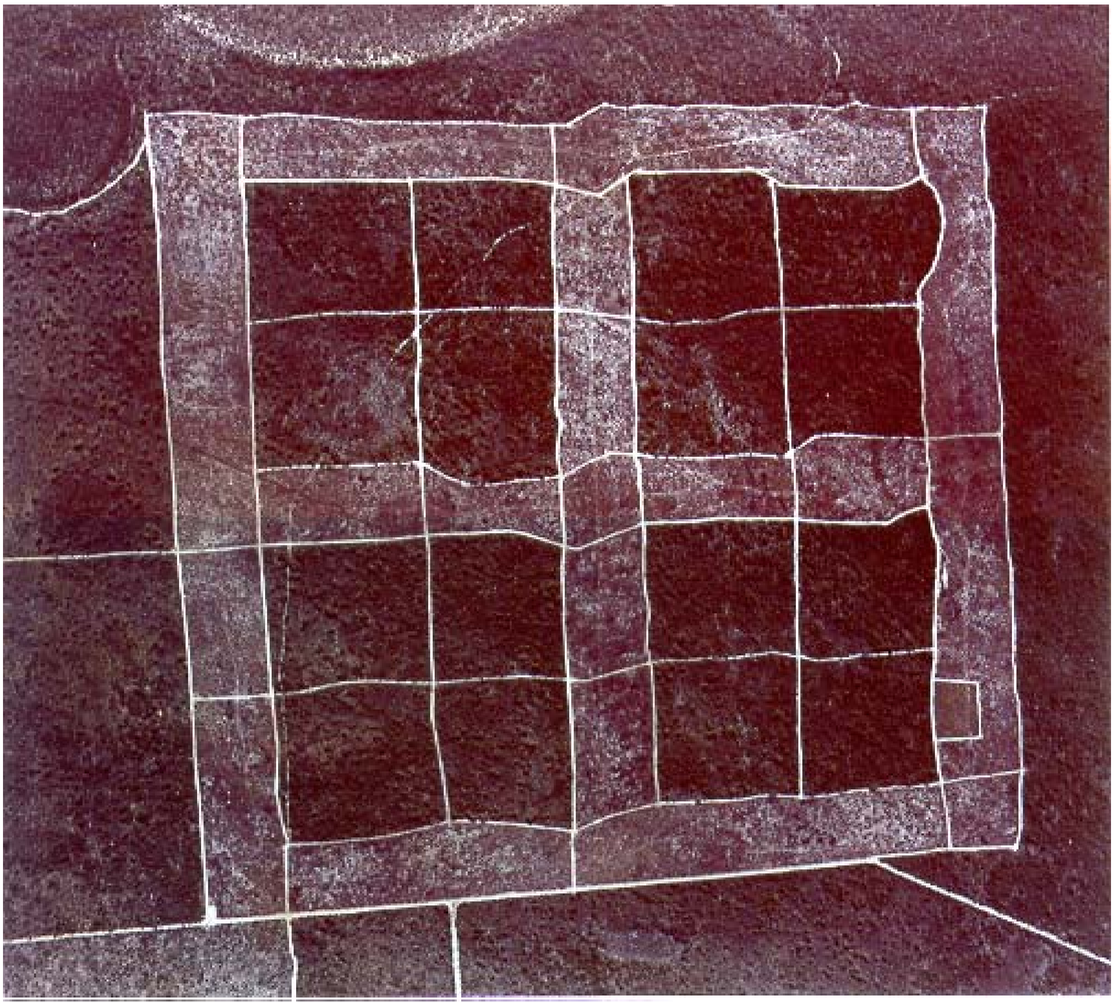


Plate 3 Aerial photograph of the experimental site taken in July 1989 showing the sixteen 200 m x 200 m plots and the 100 m wide buffer strips established by scrub-rolling and burning the vegetation.

Figure 2.3 Key to experimental plots.

A more detailed study was undertaken of flowering and seed production in relation to plant age for *Hakea crassifolia,* a tall woody shrub that is a prominent feature of the vegetation at the study site. This species was studied because it is widespread throughout mallee-heath communities in the Stirling Range National Park, is fire sensitive and appeared to have a juvenile period that was longer than most co-occurring shrubs. In February 1994, eighteen individual eight-year-old plants that had flowered for the first time in spring 1992 were marked with numbered metal tags. It was possible to retropectively identify plants that had initiated follicles as a result of flowering in 1992, but the proportion of plants that had flowered in 1992 and their height could not be established. Plants were visited annually in spring from 1994 to 1997 to measure height to growing tip and to record flowering activity and the number of seed follicles.

2.4.2 Assessment of fuel characteristics prior to experimental fires

Fuel characteristics were sampled on transects that consisted of ten consecutive 1 m^2 quadrats. Transects were marked at both ends with steel posts. Five such transects were established on a systematic pattern, as shown in Figure 2.4, within six of the experimental plots that had been selected to represent the range of vegetation types within the study area. In total, fuel characteristics were sampled on 30 transects at the study site.

Figure 2.4 Layout of transects used to sample fuels within experimental plots.

The sampling procedure adopted for measurements of vegetation was intended to provide information about vertical and horizontal variability in cover and biomass, together with several alternative measures of vegetation height (fuel bed depth). Fuel bed depth is an input variable for several fire behaviour models and appropriate values were required for mallee-heath to permit the evaluation of these models (see Chapter 5). Vegetation structure was assessed by point intercept sampling (Levy and Madden 1933, Sneeuwjagt 1971). One hundred points were sampled along each transect, at 0.1 m intervals along a tape stretched between the steel posts. At each point, intercepts with the layer of leaf litter on the ground, with bare ground, and with live and dead vegetation were recorded. Intercepts were scored in 0.2 m intervals up to 1 m height, and in 0.5 m intervals between 1.0 m and 2.5 m height; intercepts above 2.5 m height were grouped into a single class. The rod was held vertically by the observer, and care was taken to minimise deviations from the vertical alignment which may have biased the number of contacts. The height of the vegetation within each 1 m^2 quadrat was defined as the mid-point of the tallest height interval within which an intercept with live vegetation was scored. An average height of 3 m was assumed for intercepts with vegetation taller than 2.5 m. Heights for individual quadrats were also grouped to determine the 50^{th} percentile (median) and 70^{th} percentile heights for each transect. Burgan and Rothermel (1984) suggest that 70 per cent of the maximum depth (ie. height) gives a reasonable estimate of depth for shrubs and other vertically oriented fuels for fuel models used in conjunction with the BEHAVE system. Percentage litter cover within individual quadrats was determined by summing the number of intercepts with litter. For each plot, the cover of litter, live and dead vegetation was determined by summing the number of contacts with the respective components for the five transects, in each of four height classes: 0-0.4 m, 0.4-1.0 m, 1.0-2.0 m and >2.0 m. Percentage cover values for each plot were based on a sample of 500 points within height classes.

Once the point intercept sampling had been completed, dead (<25 mm diameter) and live (<6 mm diameter) plant material was harvested separately from each of the ten 1 m^2 quadrats along each transect in height classes of 0-0.4 m, 0.4-1.0 m, 1.0-2.0 m and >2.0 m. Samples of the litter layer, which included dead leaves and fine twigs (<6 mm), were also collected from ten 0.04 m^2 quadrats along each transect. Quadrats of this size are routinely used for litter sampling in fire research studies by the Department of Conservation and Land Management (for example Burrows 1994, McCaw *et al.* 1996). Litter and vegetation samples were transported to the laboratory at Manjimup and sorted prior to oven drying for 24 hours at 105°C. This drying regime was shown in a pilot study to be sufficient to achieve constant oven-dry weight for the type of fuel samples being collected, with no apparent weight loss due to the volatilisation of organic compounds. Samples from individual quadrats within each transect were weighed separately. Loadings of litter, dead fuel <25 mm, and live fuel <6 mm in each height class were determined for each transect by summing the loadings for individual 1 m^2 quadrats, and a mean loading for each plot was then calculated from the totals for the five transects. Samples from the five transects in Plot L were further sorted to determine the proportions, by weight, in the following categories for each height class:

- dead : <6 mm and 6-25 mm diameter;
- live : leaves, and stems < 2 mm, 2-4 mm, 4-6 mm diameter.

These proportions were then used as the basis for estimating the quantity of available fine fuel (dead <6 mm and live <4 mm) in the other five plots.

The average bulk density of the fuel bed, including both dead and live fuels, was calculated from the average fuel loadings in the 0-0.4 m, 0.4-1.0 m and 1.0-2.0 m height classes. Bulk density was not calculated for the >2.0 m height class because no upper height limit was specified, and thus the volume within which the fuel occurred was indeterminate.

Relationships between the frequency of contacts and the weight of each fuel component were investigated in order to assess the utility of point intercept sampling as a technique for predicting fuel loadings. Fuel loadings from the thirty 10 m x 1 m sampling transects were regressed against the frequency of contacts with litter, dead and live material within the transect using separate regressions for each height class. Prior to regression, biomass weights were square root transformed to correct for skewness. Log transformation was also considered but found to be less satisfactory than square root transformation.

2.4.3 Changes in fuel characteristics with increasing time since fire

Changes in vegetation height, cover and fuel loading during the first five years after fire were examined by sequential sampling within one of the plots (Plot G) that was burnt in February 1991. Sampling was undertaken in an area adjacent to the vegetation quadrats described in Section 2.4.1 and on a similar sandy-gravel soil type. The fire in Plot G had an estimated average frontal fire intensity of 14 000 kW m^{-1} (Section 4.5.13) and had consumed all dead fuel <25 mm diameter and live foliage and twigs ≤4 mm diameter on the standing vegetation. Following the fire, ten individually-numbered steel posts were established at 5 m intervals along a line parallel to the boundary of the plot. In March 1992, and then annually thereafter up to 1997, one post was selected at random without replacement as the starting point for a fuel sampling transect oriented perpendicular to the line of posts. At each of ten points spaced at 5 m intervals along the transect, litter fuel was collected from a 0.04 m^2 quadrat and dead fuel (<6 mm and 6-25 mm) and live fuel (<6 mm) collected from a 1 m^2 quadrat using the same height classes as during the pre-fire sampling. Samples were oven-dried and weighed to determine loadings of each fuel component. In addition, from 1994 onwards vegetation structure was also measured by the point intercept method previously described, using ten samples per quadrat to provide a total of 100 samples per transect.

The same procedures as described above were used to assess vegetation height, cover and fuel loading in a nearby area of comparable mallee-heath that had last been burnt in April 1986, and which carried ten-year-old fuel at the time of sampling. Height, loading and cover data for 20-year-old fuel were available from the sampling undertaken prior to experimental fires. Data from Plot C were not included in the average for 20-year-old fuel because the characteristics of the fuel and vegetation in this plot were quite different to those in the remainder of the area.

2.4.4 Data analysis

Relationships between variables used to describe fuel structure and loading were intially examined using scatterplots. Trends in height, loading, cover and proportion of dead fuel with increasing time since fire were examined graphically, and equations describing some of these relationships were fitted to the experimental data. Least squares regression models were fitted with the SYSTAT statistical package (SYSTAT 1992) using a weighted technique. Parameters for non linear models were estimated by the Gauss-Newton algorithm. Goodness of fit of non linear equations was assessed according to the mean absolute error (MAE) , defined as $\sum_i | y - y|/n$, and the root mean square error (RMSE), defined as $(\sum_i (y - y)^2/n)^{0.5}$, where y and y are the observed and predicted values respectively and n is the number of observations. The MAE and RMSE are alternative measures of the average error of fitting, with the MAE being less sensitive to outliers than the RMSE. Asyptotic standard errors for parameters were also determined. Differences in the number of transects used to determine the mean loadings for age classes up to ten-years-old and for 20-year-old fuels were taken into account using a weigthing factor equal to the square root of the number of observations comprising the mean for the class. Equations were fitted to untransformed fuel load data, but square root and arcsine transformation were applied to cover data prior to fitting equations.

2.5 Results

2.5.1 Vegetation structure and floristic composition

Plants from twenty two families and 50 genera were recorded in the 10 m x 10 m quadrats established to sample vegetation floristics and structure. In total, 102 plant taxa were collected prior to burning although not all could be identified to the level of species. The three most numerous families were Proteaceae (11 genera), Myrtaceae (10 genera) and Fabaceae (9 genera) (Table 2.1). Within each of these three families, more than half the genera were represented by a single taxon. Each quadrat typically contained between 50 and 60 plant taxa, with only nine taxa recorded in all 14 quadrats (Appendix A). For convenience, plants are referred to as species rather than as taxa in subsequent discussions.

Structurally, the vegetation consisted of three distinct strata:

- an upper stratum of mallee eucalypts 3 to 4 m tall, principally *Eucalyptus tetragona* and *Eucalyptus pachyloma*, with occasional *Eucalyptus marginata* and *Eucalyptus decipiens*;

- an intermediate stratum up to about 2.5 m tall of grass-trees (*Xanthorrhoea platyphylla)* and tall Proteaceous shrubs including *Hakea crassifolia*, *Dryandra falcata*, *Dryandra sessilis*, and *Lambertia inermis*. On the white sand substrates within the study area the intermediate stratum of the vegetation commonly consisted of other Proteaceous shrubs including *Banksia attenuata*, *Banksia baxteri* and *Banksia coccinea*;

- a diverse layer of low and dwarf shrubs less than 1 m tall that included species of Proteaceae (*Banksia, Dryandra, Hakea, Isopogon,* and *Petrophile*), Myrtaceae (*Beaufortia*, *Calothamnus*, *Calytrix*) and Fabaceae (*Chorizema*, *Daviesia*, *Jacksonia*).

Monocots from the Cyperaceae and Restionaceae were widespread in the the lower stratum of the vegetation but annual and perennial grasses were absent. Representative photographs of the vegetation within the study area are shown in Plate 4.

Most of the southern half of Plot C was taken up by a shallow depression. Surface water accumulated in this depression following heavy rain and it remained inundated for a period of several months in mid-1993. Vegetation in this area was characterised by occasional *E. decipiens* with a lower stratum of *Melaleuca* shrubs up to 1 m tall and a sparse ground layer of rushes and sedges (Families Cyperaceae and Restionaceae) (Plate 4). The surface litter layer was noticeably sparser in this area than elsewhere in Plot C or the remainder of the experimental site.

A small patch (50 m x 10 m) of the vegetation in the centre of Plot G was also noticeably shorter and sparser than the surrounding vegetation because it had been ignited by lightning in 1987; rain extinguished this fire before it spread extensively. Elsewhere in the study area the major variation in the structure of the vegetation was due to the presence of thickets of *B. baxteri* and *B. coccinea* on white sands. These thickets were mostly at the eastern end of the study area.

TABLE 2.1

Floristic contribution of the three most numerous families of vascular plants in 20-year-old mallee-heath at the Stirling Range study site. The height class in which the taxa most commonly occurred is also shown. A list of individual taxa is provided in Appendix A.

			Number of species by height stratum (m).			
Family	Genus	Number of taxa	0 - 0.4	0.4 - 1	1 - 2	>2
Proteaceae	*Adenanthos*	1	1	-	-	-
	Banksia	3	1	2	-	-
	Conospermum	1	1	-	-	-
	Dryandra	8	4	-	2	2
	Grevillea	1	1	-	-	-
	Hakea	6	-	3	2	1
	Isopogon	3	1	1	1	-
	Lambertia	1	-	-	-	1
	Petrophile	5	1	1	3	-
	Stirlingia	1	1	-	-	-
	Synaphea	1	1	-	-	-
Myrtaceae	*Agonis*	1	-	1	-	-
	Baeckea	1	-	1	-	-
	Beaufortia	2	-	2	-	-
	Calothamnus	4	-	4	-	-
	Calytrix	2	1	1	-	-
	Darwinia	1	-	1	-	-
	Eucalyptus	4	-	-	-	4
	Leptospermum	1	-	1	-	-
	Melaleuca	1	-	1	-	-
	Verticordia	1	1	-	-	-
Fabaceae	*Chorizema*	1	-	1	-	-
	Daviesia	2	-	2	-	-
	Gompholobium	1	-	1	-	-
	Hovea	1	-	1	-	-
	Jacksonia	1	-	1	-	-
	Oxylobium	1	-	-	1	-
	Pultenea	1	-	1	-	-
	Sphaerolobium	1	1	-	-	-

Plate 4(a) Mallee-heath vegetation at the Stirling Range study site showing fuel sampling transect 2 in Plot K before and after experimental burning; note that removal of fuel from the 10 m x 1 m transect has not appreciably altered the extent of fuel consumption in adjacent areas.

Plate 4(b) Mallee-heath vegetation at the Stirling Range study site showing fuel sampling transect 2 in Plot J before experimental burning, and the sparse vegetation which occurred in the central part of Plot C.

Plants were grouped into categories based on life form and potential height at maturity, as follows: mallees; tall shrubs > 1 m in height; low shrubs 0.4 - 1.0 m; dwarf shrubs < 0.4 m; other non-shrub dicots; and Restionaceae, Cyperaceae, and other monocots. These categories correspond closely with the categories employed by Van Wilgen (1982b) to examine the relative importance of different life forms in 21-year-old fynbos shrubland at Jonkershoek, South Africa. Van Wilgen (1982b) assigned percentage cover values to estimates made using a cover abundance scale and accumulated the cover values for each life form to give a numerical measure of relative importance. The same technique was applied to the data listed in Appendix A, allowing the relative importance of different life forms to be compared between mallee-heath and fynbos shrubland. Modal cover abundance ratings for each species were related to percentage cover as follows: 1 and 2 = 0.5 per cent cover, 3 = 2.5 per cent cover, 4 = 7.5 per cent cover and 5 = 17.5 per cent cover. The structure of the cover abundance scale used in this study was similar to that used by Van Wilgen (1982b) but differed slightly in the ratings applied to classes of percentage cover. In the fynbos study, the boundary between the low shrubs and dwarf shrubs was set at 0.25 m rather than 0.4 m. Comparative data for 20-year-old mallee-heath and 21-year-old fynbos are presented in Table 2.2.

The total of the relative importance values for all life forms was substantially lower in mallee-heath than in fynbos (Table 2.2). This probably reflects the lower overall level of plant cover in this community, but might also partly be due to differences in the cover abundance scales employed for each study and the way in which these were converted to percentage cover scores. Low and dwarf shrubs were the dominant life forms in the mallee-heath community, followed by tall shrubs and mallee eucalypts. Fifty eight of the plant species recorded in the quadrats were classified as low or dwarf shrubs. The dominant ranking of the low shrubs was not altered even if the relative importance values for the mallee eucalypts and the tall shrubs were combined. Restionaceae, Cyperaceae and other monocots were the least important life forms in mallee-heath and contributed only 10 per cent of the total importance score for the plant community. Tall shrubs were the most important life form in the fynbos community, with the next most important group being an unspecified group of plants that were neither shrubs, Restionaceae or Cyperaceae. In contrast with mallee-heath, Restionaceae and Cyperaceae had similar importance values to dwarf shrubs in the fynbos community.

TABLE 2.2

Relative importance of plant life forms in 20-year-old mallee-heath and 21-year-old fynbos.

Life form	Mallee-heath			Fynbos		
	Importance value	Rank	% of total	Importanc e value	Rank	% of total
Mallee (or trees)	17.5	4	10	0.1	7	< 0.1
Tall shrubs (> 1.0 m)	27.0	3	15	121.6	1	39
Low shrubs (0.4 - 1.0 m)	71.0	1	40	48.8	3	6
Dwarf shrubs (< 0.4 m)	36.5	2	21	19.6	5	6
Restionaceae	3.5	8	2	17.3	6	6
Cyperaceae	6.0	7	3	20.9	4	7
Other dicots	6.5	6	4			
Other monocots	9.0	5	5			
Other (unspecified)				82.0	2	26
Total	177.0		100	310.3		100

The eucalypts which formed the tallest stratum of the mallee-heath community re-sprouted after fire, either from epicormic shoots beneath the bark (*E. marginata* and *E. decipiens*) or from basal shoots originating from woody lignotubers (*E. pachyloma* and *E. tetragona*) (Table 2. 3). In contrast, most tall shrubs were fire-sensitive and regenerated from seed stored on the mature plant. Some of these tall shrubs accumulate a substantial store of seed in woody capsules and follicles that only open following death of the plant (eg. *H. crassifolia*), while others require heat to open the follicles (eg. *B. baxteri*). Further details of seed release mechanisms for these shrubs are provided by McCaw and Smith (1992). Other species, such as *L. inermis*, have thin-walled capsules and tend to release seed each year.

Low shrubs were mostly either fire-sensitive species which regenerated from soil-stored seed, or species which re-sprouted from basal shoots (Table 2.3). Dwarf shrubs mostly regenerated from soil-stored seed. A few of the low and dwarf shrubs were fire sensitive plants with canopy stored seed. A small proportion of plants regenerated from corms, bulbs, rhizomes and intact terminal buds. The response strategies of a small number of taxa could not be determined because they occurred in areas that remained unburnt.

TABLE 2.3

Representation of post-fire plant response strategies by height class in 20-year-old mallee-heath. Response strategies for woody plants are those proposed by Gill (1981).

Response strategy	Number of species by height stratum:				Total
	0 - 0.4 m	0.4 - 1.0 m	1.0 - 2.0 m	>2.0 m	
Plants die following crown scorch and regenerate from:					
- seed in capsules on plant	2	6	7	2	17
- seed in the soil	18	16	-	-	34
- seed storage uncertain	3	-	-	-	3
Plants recover following crown scorch from:					
- root suckers and rhizomes	1				1
- basal stem sprouts	6	14	2	2	24
- epicormic buds	-	-	-	2	2
-active terminal buds	3	-	1	-	4
- corms and bulbs	6	-	-	-	6
Response strategy unknown	6	3	2	-	11
Total	45	39	12	6	102

Fire sensitive plants with capsule-stored seed had primary juvenile periods which ranged from a minimum of 3 years for *Beaufortia schaueri*, a common low shrub, to at least 7 years or more for tall *Hakea* and *Petrophile* shrubs (Figure 2.5).

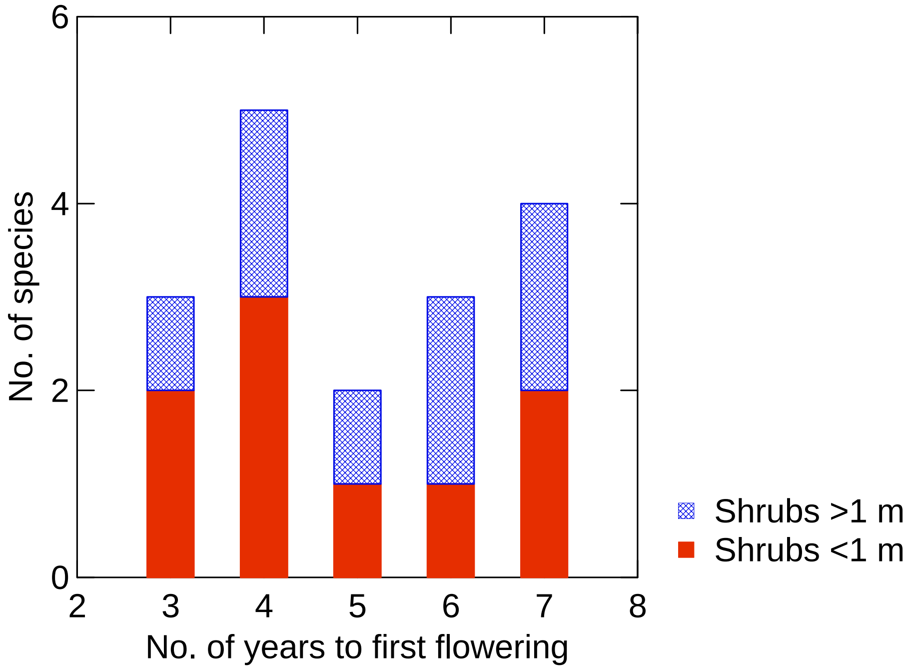


Figure 2.5 Primary juvenile periods for fire sensitive shrubs >1 m and <1 m tall which store seed in capsules or follicles on the plant.

H. crassifolia flowered for the first time at an age of six years after fire, from which two of the 18 plants subsequently produced follicles. Forty per cent of the marked shrubs had flowered after eight years, and the proportion increased over subsequent years with all plants flowering after ten years (Table 2.4). The proportion of shrubs carrying mature seed follicles increased from 40 per cent at an age of eight years to 72 per cent at 11 years. Eleven-year-old plants that had fruited successfully carried a median number of four follicles which is equivalent to a store of eight seeds per plant, each mature follicle containing two seeds (McCaw and Smith 1992).

TABLE 2.4

Proportion of *H. crassifolia* with flowers and seed follicles in relation to time since fire determined from periodic observations on a sample of 18 plants. The median number of follicles on plants that had fruited successfully is also shown. Plant heights are means, with the range in brackets.

Plant age (years)	Height (m)	Percentage of plants: Flowered	Fruited	Median number of follicles per plant
7	n.d	n.d	11	1
8	1.35 (0.65 - 2.07)	40	40	4
9	1.52 (0.95 - 2.44)	88	67	3
10	1.49 (0.55 - 2.53)	100	67	3
11	1.62 (0.98 - 2.70)	100	72	4

n. d. = not determined

2.5.2 Fuel characteristics prior to experimental fires

The 50th and 70th percentile heights of live shrubs in 20-year-old mallee heath were 0.8 m and 1.8 m respectively (Table 2.5). Within individual plots, 50th percentile heights ranged from 0.7 m to 1.3 m, and 70th percentile heights from 1.3 m to 2.3 m. Excluding data from Plot C increased the 50th height to 0.9 m, but did not alter the 70th percentile height.

The average fuel loading for the site was 1.24 kg m^{-2} which included litter, dead fuel <25 mm and live fuel <6 mm. Loadings within individual plots ranged from 0.87 kg m^{-2} in Plot C to 1.48 kg m^{-2} in Plot N (Table 2.6). On average, 36 per cent of the total loading was litter, 25 per cent was dead fuel and 39 per cent was live fuel. Most of the dead fuel occurred within the low shrub layer, with 67 per cent in the 0-0.4 m height class and a further 19 per cent in the 0.4-1.0 m height class (Figure 2.6). There was very little dead fuel present above 2 m height. At least 67 per cent of the dead loading within each height class up to 2.0 m consisted of fine fuel particles <6 mm in diameter comprised (Tables 2.7 and 2.8).

TABLE 2.5

Height of live shrubs in 20-year-old mallee-heath as indicated by the 50th and 70th percentiles. The range of heights for the five transects in each plot shown in brackets.

Percentile	Live shrub height (m) by plot:						
	Plot C	Plot I	Plot J	Plot K	Plot L	Plot N	Median
50th	0.7	0.9	1.3	1.1	0.7	1.3	0.8
	(0.6-1.1)	(0.6-3.0)	(0.5-2.0)	(0.6-2.4)	(0.4-1.8)	(1.3-2.3)	
70th	1.3	2.3	1.8	1.8	1.3	1.8	1.8
	(0.7-3.0)	(1.3-3.0)	(1.3-3.0)	(0.5-3.0)	(0.9-1.8)	(1.3-3.0)	

Loadings of live shrub components <6 mm ranged from 0.38 kg m^{-2} to 0.61 kg m^{-2} (Table 2.6). Forty six per cent of the live fuel load occurred in the 0-0.4 m height class and a further 25 per cent in the 0.4-1.0 m class (Figure 2.6). The detailed sorting undertaken for Plot L revealed considerable differences in the distribution of various components of the live fuel between height classes (Table 2.7 and 2.8). Leaves made up a relatively small proportion (<20 per cent) of the sample live fuel load below 1.0 m height, but increased to 38 per cent of sample load in the 1.0-2.0 m height class due to the contribution of shrub canopies (Table 2.8). In contrast, the proportion of live fuel in the sample contributed by twigs <2 mm declined progressively with increasing height. This was most probably a reflection of the presence of larger leaves on taller shrubs and mallee eucalypts. Twigs 2-4 mm in diameter made up a relatively constant proportion of the live fuel load in all height classes (26-36 per cent) as did twigs 4-6 mm diameter (16-23 per cent). Based on these values, leaves and fine twigs <4 mm diameter were estimated to comprise 84 per cent, 82 per cent and 77 per cent of the live fuel loading in the 0-0.4, 0.4-1.0 and 1.0-2.0 m height classes respectively.

TABLE 2.6

Loading (kg m^{-2}) of litter, dead (<25 mm) and live (<6 mm) fuel by height class for six experimental plots in 20-year-old mallee-heath. Data are means and standard deviations (in brackets) for five 10 m x 1 m sample transects within each plot

		Loading (kg m^{-2})						
Height Class (m)	Component	Plot C	Plot I	Plot J	Plot K	Plot L	Plot N	Mean for all plots
0 - 0.4	Litter	0.28 (0.33)	0.47 (0.16)	0.55 (0.25)	0.40 (0.20)	0.48 (0.30)	0.49 (0.15)	0.45
	Dead	0.16 (0.08)	0.28 (0.09)	0.25 (0.07)	0.17 (0.04)	0.18 (0.03)	0.22 (0.04)	0.21
	Live	0.22 (0.08)	0.24 (0.05)	0.26 (0.06)	0.18 (0.06)	0.18 (0.06)	0.25 (0.06)	0.22
0.4 - 1.0	Dead	0.03 (0.03)	0.05 (0.04)	0.05 (0.03)	0.07 (0.08)	0.06 (0.03)	0.08 (0.04)	0.06
	Live	0.08 (0.04)	0.09 (0.02)	0.16 (0.06)	0.10 (0.05)	0.11 (0.04)	0.19 (0.02)	0.12
1.0 - 2.0	Dead	0.02 (0.02)	0.02 (0.03)	0.03 (0.03)	0.06 (0.07)	0.03 (0.03)	0.07 (0.09)	0.04
	Live	0.05 (0.06)	0.08 (0.10)	0.09 (0.06)	0.09 (0.09)	0.13 (0.09)	0.12 (0.06)	0.09
>2.0	Dead	0	0.03 (0.03)	<0.01	<0.1	<0.1	0.01 (0.01)	n.d.
	Live	0.03 (0.06)	0.10 (0.09)	0.06 (0.06)	0.05 (0.10)	0.03 (0.03)	0.05 (0.04)	0.05
All Heights	Litter	0.28	0.47	0.55	0.40	0.48	0.49	0.45
	Dead	0.21	0.38	0.33	0.30	0.27	0.38	0.31
	Live	0.38	0.51	0.57	0.42	0.44	0.61	0.48
	Total	0.87	1.36	1.45	1.12	1.19	1.48	1.24

TABLE 2.7

Loading (kg m^{-2}) of dead (D) and Live (L) fuel components by diameter class (in mm) for five sample transects from Plot L.

Height Class (m)	Fuel Component	Transect 1	Transect 2	Transect 3	Transect 4	Transect 5	Mean	Std. Dev.
0 - 0.4	D <6	0.12	0.17	0.12	0.11	0.16	0.14	0.03
	D 6-25	0.01	0.05	0.07	0.05	0.03	0.04	0.02
	L Leaves	0.05	0.03	0.02	0.02	0.05	0.03	0.01
	L <2	0.09	0.07	0.10	0.11	0.04	0.08	0.03
	L 2-4	0.06	0.07	0.03	0.05	0.02	0.05	0.02
	L 4-6	0.03	0.03	0.03	0.03	0.01	0.03	0.01
0.4 - 1.0	D <6	0.01	0.06	0.04	0.07	0.05	0.05	0.02
	D 6-25	<0.01	0.02	0.03	0.01	0.01	0.01	0.01
	L Leaves	0.02	0.01	0.01	0.04	0.03	0.02	0.01
	L <2	0.03	0.03	0.03	0.04	0.02	0.03	0.01
	L 2-4	0.04	0.07	0.02	0.05	0.01	0.04	0.02
	L 4-6	0.02	0.03	0.01	0.03	0.02	0.02	0.01
1.0 - 2.0	D <6	0.01	0.01	<0.01	0.01	0.06	0.02	0.02
	D 6-25	0.01	0	<0.01	0.04	0.01	0.01	0.02
	L Leaves	0.02	0.05	0.01	0.07	0.10	0.05	0.04
	L <2	0.01	<0.01	<0.01	0.01	0.02	0.01	0.01
	L 2-4	0.02	0.07	<0.01	0.05	0.06	0.04	0.03
	L 4-6	0.01	0.03	<0.01	0.12	0.06	0.03	0.02
>2.0 m	D <6	0	0	0	<0.01	<0.01	<0.01	<0.01
	D 6-25	0	0	0	0.01	0	0.01	0.01
	L Leaves	0.03	0	0.1	0.04	0.01	0.02	0.02
	L <2	<0.01	0	<0.01	<0.01	<0.01	<0.01	<0.01
	L 2-4	0.02	0	<0.01	0.01	<0.01	0.01	0.01
	L 4-6	0.01	0	<0.01	0.01	<0.01	0.01	<0.01

TABLE 2.8

Proportions of dead (D) and live (L) fuel by diameter class (in mm) for height classes up to 2.0 m above ground, determined for Plot L. The fine fuel fraction was assumed to comprise dead fuel <6 mm and live leaves and twigs <4 mm diameter.

Height Class (m)	Dead		Live			
	D <6	D 6 - 25	L Leaves	L <2	L 2 - 4	L 4 - 6
0 - 0.4	0.78	0.22	0.16	0.42	0.26	0.16
0.4 - 1.0	0.83	0.17	0.18	0.27	0.36	0.18
1.0 - 2.0	0.67	0.33	0.38	0.08	0.30	0.23

TABLE 2.9

Cover (per cent) of litter, and dead and live fuel by height class for six plots in 20-year-old mallee-heath. Based on 500 point intercept samples in each plot.

		Cover (per cent)						
Height Class (m)	Component	Plot C	Plot I	Plot J	Plot K	Plot L	Plot N	Mean for all plots
0 - 0.4	Litter	58	80	83	74	77	72	74
	Dead	39	55	58	38	44	63	50
	Live	54	53	69	54	49	77	59
0.4 - 1.0	Dead	5	9	9	16	13	21	12
	Live	15	16	27	19	17	43	23
1.0 - 2.0	Dead	2	5	4	5	5	12	6
	Live	4	9	15	16	11	25	13
>2.0	Dead	3	2	<1	1	1	1	1
	Live	4	8	9	10	3	7	7

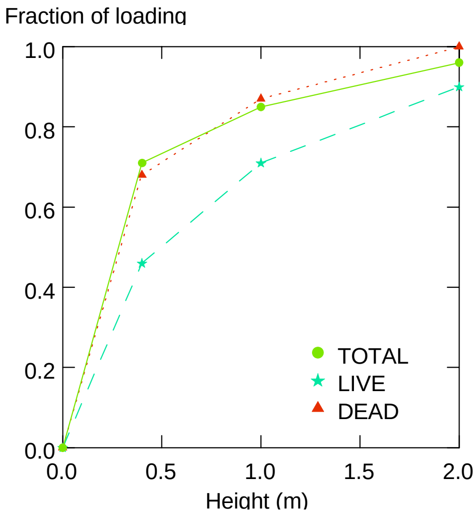


Figure 2.6 Cumulative distribution showing the fraction of the loading of dead fuel <25 mm, live fuel <6 mm and total fuel in relation to height above ground.

To estimate the quantity of fine fuel available for combustion in the flaming zone, an assumption must be made how much of the live fuel will be consumed. Under typical burning conditions the amount of fine fuel available would include 0.48 kg m^{-2} of litter, 0.26 kg m^{-2} of dead fuel <6 mm and 0.41 kg m^{-2} of live fuel <4 mm, making up a total of 1.15 kg m^{-2}. For severe burning conditions when live fuels up to 6 mm might be consumed, the available fuel loading increases to 1.25 kg m^{-2}. Dead fuel 6-25 mm is unlikely to be consumed in the flaming zone of a spreading fire and is therefore not considered to be available fine fuel. However, it is consumed by glowing and smouldering combustion after the flames have passed, and can contribute substantially to the total energy released by a fire.

For each height class, the loading of dead fuel <6 mm was expressed as a fraction of the combined loading of live and dead fuel; in the case of the 0-0.4 m height class, the litter was included as part of the dead fuel load. The dead fuel fraction declined with increasing height, from a mean of 0.73 in the 0-0.4 m class to a mean of 0.12 for heights above 2.0 m (Figure 2.7). The relationship between dead fuel fraction and height was described using a power function fitted using least squares regression, as follows:

$$D_f = 0.243\ Height_m^{\ -0.748} \qquad (2.1)$$

where D_f is the arcsine transformed fraction of dead fuel <6 mm diameter and $Height_m$ is the height class mid-point, in m. Asymptotic standard errors for the coefficients were respectively 0.017 and 0.049, and the MAE and RMSE were 0.044 and 0.063 respectively. An exponential function was also examined, but found not to fit the data as well as the power function.

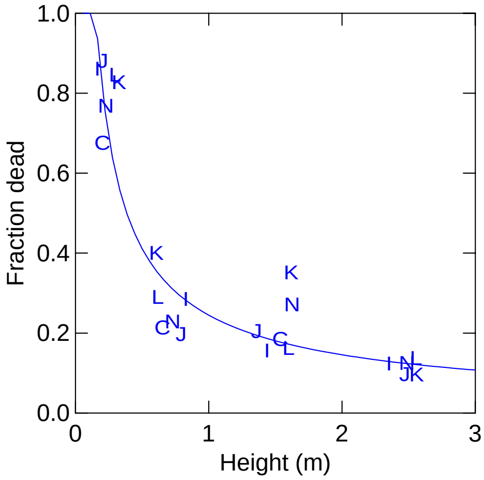


Figure 2.7 Fraction of the total fuel loading comprised of litter and dead fuel <25 mm in relation to height above ground. Letters indicate the dead fuel fractions for the six plots, and heights are the mid-points of the classes used for fuel sampling. The fitted line is Equation 2.1.

The proportion of ground area covered by litter averaged 74 per cent with a range from 58 per cent to 83 per cent (Table 2.9). Cover of dead and live vegetation was greatest in the low shrub layer (0-0.4 m height class) with means of 50 and 59 per cent respectively. Both live and dead cover declined progressively with increasing height. Relative proportions of dead and live cover also varied with height, being similar in the 0-0.4 m height class but with live cover predominating above this level.

Plot C had the lowest total fuel loading, as well as the lowest loadings for each component of the fuel (Table 2.6). The litter loading was substantially more variable in Plot C than was the case in the other five plots, with the co-efficient of variation being 1.17 in Plot C but only between 0.31 and 0.50 in the remaining plots. Loadings of litter, dead and live fuel were compared between Plot C and the other five plots using the separate variance *t* test procedure available in the SYSTAT statistical package (SYSTAT 1992). This testing procedure is appropriate when the variances of the two groups are unequal, as was the case here. Loadings of litter and live fuel were not significantly different ($P > 0.05$) between Plot C and the other plots, but dead fuel loading was significantly lower in Plot C ($P = 0.02$). Plot C also had the lowest proportion of ground area covered by litter, with 58 per cent cover compared to values in the range 72-83 per cent for the remaining plots.

Loadings of litter, dead and live fuel in each height class were significantly correlated with the frequency of point contacts for the respective fuel components, except for dead fuel in the 0-0.4 m height class (Table 2.10). Correlation co-efficients for dead fuel ranged from 0.338 (not significant) to 0.617 ($P \leq 0.001$) and were of similar magnitude for the three height classes above 0.4 m. Correlations coefficients for live fuel were consistently stronger than for dead fuel in the same height class, and were stronger for height classes above 0.4 m. Litter fuel loading was strongly correlated with point intercept density.

TABLE 2.10

Pearson correlation coefficients between biomass loading (square root transformed) and frequency of contacts with litter, dead and live fuel components recorded from point intercept sampling on fuel transects. The number of observations used to calculate correlation coefficients in each height class is shown *(in brackets)*. Litter was only present in the 0-0.4 m height class.

Height class (m)	Correlation coefficient (r)		
	Litter	Dead	Live
0 -0.4	0.790*** *(30)*	0.338 n.s. *(30)*	0.557*** *(30)*
0.4 - 1.0	-	0.581*** *(30)*	0.769*** *(30)*
1.0 - 2.0	-	0.617*** *(26)*	0.708*** *(28)*
>2.0	-	0.564* *(15)*	0.788*** *(21)*

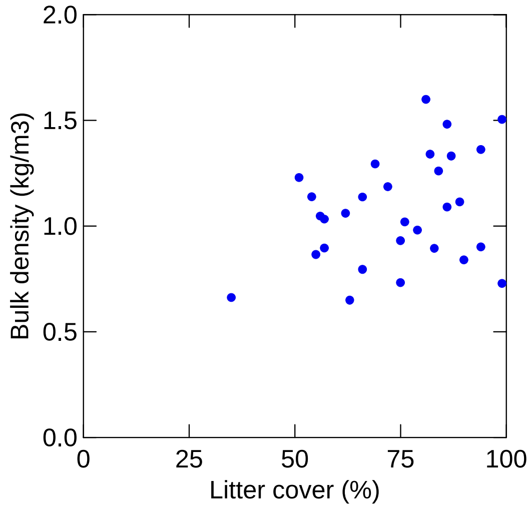
n.s. = not significant at P=0.05
* = significant at $P \leq 0.05$
*** = significant at $P \leq 0.001$

The bulk density of the fuelbed was determined from the loadings of live fuel <6 mm and dead fuel <25 mm for the three height classes up to 2 m. Profile diagrams which displayed the bulk density of the fuelbed within individual quadrats were prepared using data for the five transects in Plots C and I (Figure 2.8). These particular plots were selected because they represented, respectively, the lowest and average levels of vegetation density within the study area. Initial attempts to display dead and live fuels separately were found to be too complicated to be readily interpreted. Percentage litter cover within each quadrat is also shown on the diagrams. Within individual quadrats, the bulk density of the fuel was almost always greatest in the 0-0.4 m height class and declined with increasing height. This reflects the pattern of mean fuel loadings within height classes as summarised in Table 2.6. In a few instances bulk density was greater in the 1-2 m height class than below this height because individual quadrats included a dense shrub canopy. In Plot I the bulk density of the 0-0.4 m height class was consistently greater than 0.5 kg m^{-3}, and exceeded 1.0 kg m^{-3} in 41 out of 50 quadrats. In contrast, Plot C had 12 quadrats in the 0-0.4 m height class with bulk density $\leq$0.5 kg m^{-3} and 28 out of 50 quadrats had bulk density less than 1.0 kg m^{-3}. No more than two adjacent quadrats from any transect in Plot C had a bulk density exceeding 0.5 kg m^{-3} in the 0-0.4 m height class.

FIGURE 2.8 PLOT C

FIGURE 2.8 PLOT I

Examination of data from the 30 fuel sample transects revealed that the bulk density of the fuelbed in the 0-0.4 m height class was weakly correlated with litter fuel loading (r = 0.358, P = 0.05) but not significantly correlated with litter cover (r = 0.334, P = 0.07). Litter loading and cover are plotted in relation to bulk density in Figure 2.9.



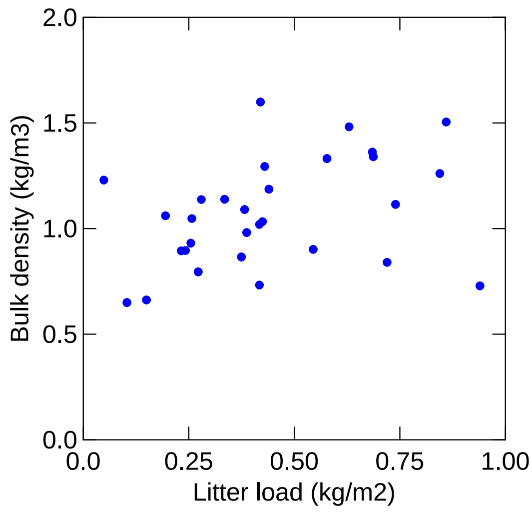


Figure 2.9 Litter cover and loading in relation to the bulk density of the fuel bed in the 0-0.4 m height class for 30 fuel sample transects.

Litter cover and loading were also examined in relation to the 70th percentile vegetation height in individual quadrats. Litter cover was consistently 65 per cent or greater where the height of the vegetation exceeded 1.5 m, but exhibited greater variability where vegetation height was lower than 1.5 m. Eight of the transects with a 70th percentile vegetation height below 1.5 m had litter cover of less than 60 per cent. Litter cover was related to vegetation height by the following equation fitted using non linear regression:

$$Cover = 1.08\,(1 - \exp(-1.14\,Height_{70})) \qquad (2.2)$$

where *Cover* is the per cent cover of litter (arcsine transformed) and $Height_{70}$ is the 70th percentile vegetation height, in m. Asymptotic standard errors for the coefficents were respectively 0.112 and 0.343, and the MAE and RMSE were respectively 0.182 and 0. 223.

Litter loading increased in an approximately linear fashion with increasing vegetation height (Figure 2.10). Linear regression models fitted to untransformed and log transformed data provided a similar fit and scatter of residuals. The model based on untransformed data was as follows:

$$Loading = 0.11 + 0.197\,Height_{70} \qquad r^2 = 0.41,\ P<0.001 \qquad (2.3)$$

where *Loading* is litter loading in kg m^{-2} and $Height_{70}$ is as previously defined.

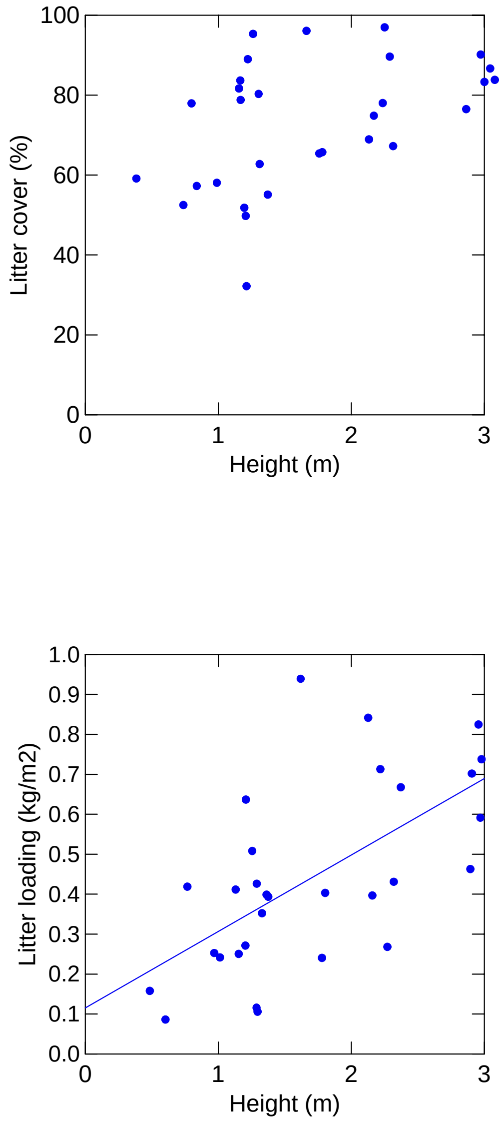


Figure 2.10 Litter cover and loading in relation to 70th percentile vegetation height for 30 fuel sampling transects. Overlapping points have been offset by a small amount. Fitted lines are equation 2.2 for litter cover and equation 2.3 for litter loading.

2.5.3 Changes in fuel characteristics with increasing time since fire

During the first two years after fire, the largest component of the fuel was dead wood 6-25 mm in diameter; this material represented the stems of the woody vegetation that had been killed by the fire (Figure 2.11). Loadings of this component declined for several years afterwards, probably due to decay and termite activity, and is the reason why the total fuel loading was less after two years than after one year since fire. The combined loading of litter and dead fuel <6 mm was very low (<0.07 kg m^{-2}) during the first two years after fire because dead fine fuel components had been completely consumed by the fire, and because the vegetation was young and contained very little dead material. Loadings of litter and dead fuel <6 mm increased progressively with time since fire, and were greatest in the 20-year-old fuel. Live fuel load increased steadily for the first four years after fire, but exhibited a distinct peak in the fifth year. This peak probably reflects variability between sampling transects rather than an age-related effect on the vegetation; the large standard error of the samples from the fifth year are consistent with this interpretation. Live fuel loading and total fuel loading differed by only a small amount (0.03 kg m^{-2}) between 10-year-old and 20-year-old vegetation. The greatest difference apparent between the 10-year-old and the 20-year-old fuel was the heavier litter loading in the older fuel.

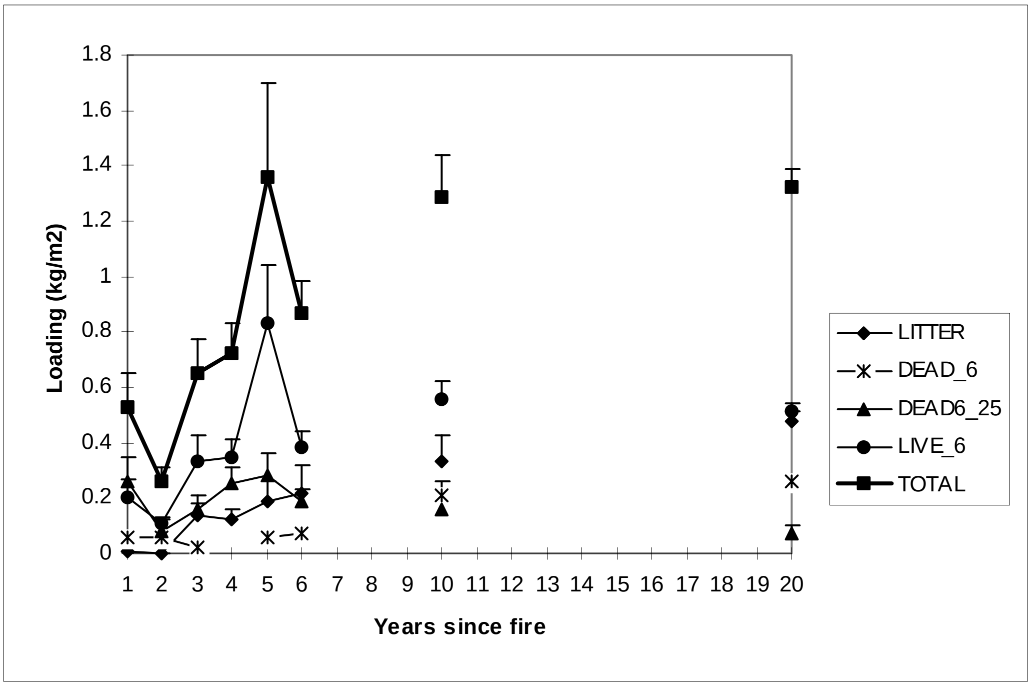


Figure 2.11 Fuel accumulation in mallee-heath from 1 to 20 years after fire. Component loadings are shown for litter, dead fuel <6 mm and 6-25 mm in diameter, live fuel <6 mm diameter, and the total of all components. Standard errors of the mean are indicated by one-sided error bars.

Accumulation of total fuel load and of individual components of the fuel was described using equations of the form:

$$L = \mathrm{a}\ (1- \exp\ (-\mathrm{b}\ t)) \qquad (2.4)$$

where L is the loading in kg m^{-2}, t is the number of years since fire, and a and b are constants. Equations of this form have been widely used to model litter and other fuel accumulation in plant communities after fire (Jenny *et al*. 1949, Olsen 1963, Fox *et al*. 1979, Birk and Simpson 1980, Raison *et al*. 1983, Conroy 1993, Fogarty 1993, Burrows 1994, Marsden-Smedley and Catchpole 1995a, McCaw *et al*. 1996) and have also been used to predict dynamic changes in fuel composition over time (O'Connell 1987). Fitting an equation of this form to the mallee-heath data involves a slight simplication in ignoring the fact that fuel loadings were higher in the first year than the second year after fire. This simplification has no real practical implications, and was considered preferable to employing a more complex and less widely accepted equation form. Equations were fitted using non linear least squares regression. Parameter estimates, asymptotic standard errors, and error statistics for equations fitted to the various components of the fuel are given in Table 2.11. Changes in the loading of dead fuel 6-25 mm diameter over time were not satisfactorily described by an equation of the form of 2.3. As dead fuel 6-25 mm diameter does not contribute directly to the available fine fuel loading, it was not considered necessary to develop a separate equation for this component.

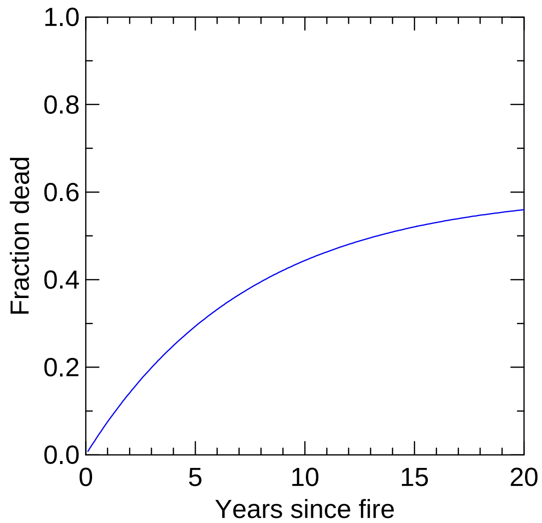


Figure 2.12 Fraction of total fuel contributed by litter and dead fuel <6 mm as a function of time since fire. The equation for the fitted line is shown in Table 2.11.

The fraction of the total fuel loading contributed by litter and dead fuel <6 mm increased progressively with time since fire and approached 60 per cent in 20-year-old fuels (Figure 2.12). Equations of the form 2.4 were used to describe fraction dead as a function of time since fire and were fitted to both raw and arcsine transformed data; equations based on untransformed data give a superior fit with lower standard errors for parameter estimates and smaller MAE and RMSE values. The equation fitted to the raw data is shown in Table 2.11. The combined loading of litter and dead fuel <25 mm however showed little relationship with time since fire and remained between 39 per cent and 61 per cent from the first year after fire onwards. Dead fuel 6-25 mm made up the majority of the dead fraction in the first five years after fire but became of secondary importance to litter and dead fuel <6 mm in fuels that were ten years old, or older.

TABLE 2.11

Equations describing changes in fuel height, loading, fraction of dead fuel and cover with increasing time since fire. All equations are of the form y = a (1- exp (-b t)), where y is the fuel attribute, t is the number of years since fire and a and b are parameters fitted using non linear least squares regression. Asymptotic standard errors for parameters are shown in brackets.

Fuel attribute	Parameter estimate (std. err.)		MAE	RMSE
	a	b		
Height				
50th percentile	0.925 (0.086)	0.323 (0.239)	0.291	0.471
70th percentile	1.760 (0.070)	0.264 (0.078)	0.229	0.347
Loading				
Litter	0.664 (0.100)	0.064 (0.019)	0.028	0.037
Dead <6 mm	0.462 (0.259)	0.041 (0.036)	0.030	0.034
Live <6 mm	0.516 (0.036)	0.403 (0.200)	0.107	0.156
Total	1.331 (0.052)	0.252 (0.062)	0.167	0.207
Fraction dead	0. 601 (0.036)	0.134 (0.033)	0.044	0.060
Cover				
Litter	0.774 (0.016)	0.244 (0.040)	0.054	0.070
Dead (<0.4 m)	0.754 (0.166)	0.063 (0.027)	0.046	0.065
Live (<0.4 m)	0.640 (0.025)	0.832 (0.714)	0.181	0.217
Live (0.4 - 1.0 m)	0.247 (0.019)	0.558 (0.500)	0.152	0.186
Live (>1.0 m)	0.270 (0.089)	0.110 (0.110)	0.202	0.282

Trends in the cover of litter, dead and live vegetation with increasing time since fire are shown in Figure 2.13, and equations describing these relationships are shown in Table 2.11. Trends in the cover of dead fuel >0.4 m height were not be adequately described by an equation of the same form as fitted to the other fuel components, and so only the raw data points are shown in Figure 2.13. For clarity of presentation, cover from several height classes have been combined. Litter cover continued to increase up to 20 years after fire, as did the cover of dead in both height groupings. Live cover peaked in the fifth year after fire, and was only slightly greater in the 20-year-old fuel than in the 10-year-old fuel. Trends in live cover over time were similar for each height class.

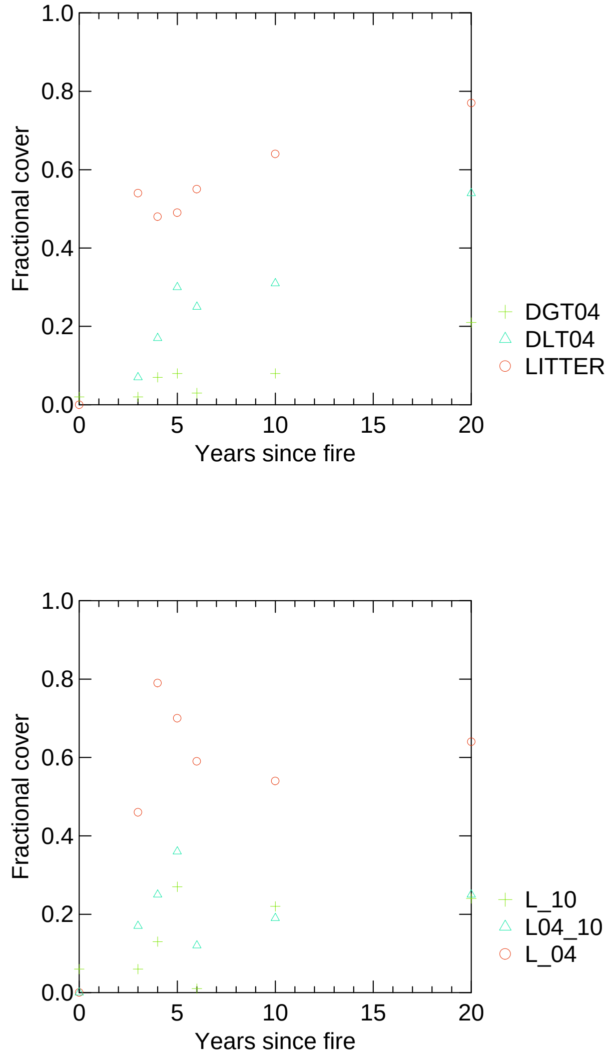


Figure 2.13 Changes in the cover of (a) litter and dead and (b) live fuel components with increasing time since fire. Cover values are shown for the following height classes: dead fuels 0-0.4 m (DLT04) and above 0.4 m (DGT04), and live fuels 0-0.4 m (L_04), 0.4-1.0 m (L04_10) and above 1.0 m (L_10).

Vegetation height growth was most rapid during the first five years after fire, with both the 50th and 70th percentile heights exceeding 1 m at age five (Figure 2.14). The 70th percentile height only increased 0.25 m between 5 and 20 years after fire. The apparent peak in the 50th percentile height ten years after fire is more likely to be a reflection of sample variability than a genuine decline between 10 and 20 years after fire. Equations describing live fuel height as a function of time are shown in Table 2.11.

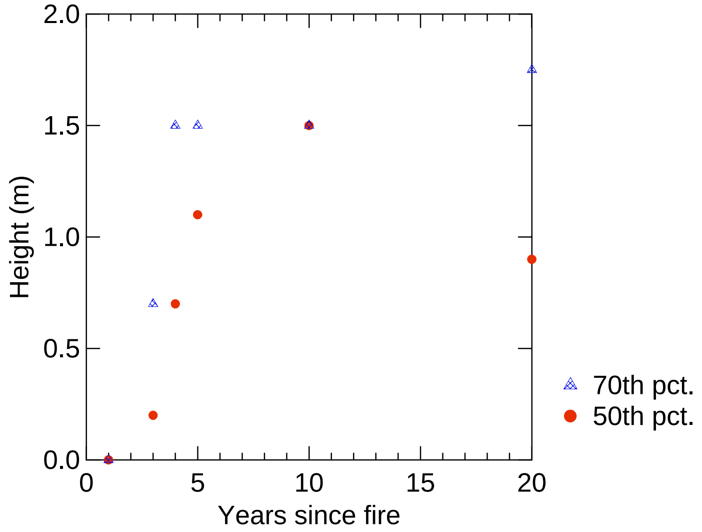


Figure 2.14 50th and 70th percentile heights for live vegetation in relation to time since fire.

2.6 Discussion

The mallee-heath plant community in the Stirling Range study area was characterised by a high level of floristic richness and structural heterogeneity. Indeed, the vascular plant flora of the study area is considerably richer than that sampled by the fourteen 10 m x 10 m quadrats, but the task of documenting the complete flora was beyond the scope and objectives of the present study. Sandplain shrublands in south-western Australia are recognised for their floristic richness which is comparable to, and sometimes exceeds that of mediterranean shrublands on other continents (George *et al*. 1979, Naveh and Whittaker 1979, Lamont *et al*. 1983). The Stirling Range is prominent as one of two nodes of great species richness in south-western Australia, the second being the Mt Lesueur-Eneabba area on the sandplain north of Perth (Lamont *et al*. 1983). Lamont *et al*. (1983) identified several notable features of sandplain shrublands in the south-west including the high number of species found in any one sample (alpha diversity) and the high turnover of species between contiguous samples and landscape units (beta and delta diversity, respectively). Overall plant diversity at the landscape scale tends, however, to be lower than recorded for mountainous regions such as the Cape fynbos in South Africa (Kruger and Taylor 1979). This is probably because the number of ecologically distinct communities in the landscape is limited in the relatively subdued topography of south-western Australia.

More than half of the plant species recorded in the quadrats were shrubs <1 m tall. Shrubs <1m tall also contributed the greater proportion of the cover and fuel loading. Many of these shrubs grow to sufficent size to make an appreciable contribution to the height, cover and loading of the fuelbed, and no particular species or genera could be regarded as being dominant. *Dryandra drummondii* was the most ubiquitous shrub <1 m tall and was present in all 14 quadrats; it also had the highest modal cover recorded for a shrub (rating of 5), which corresponds to cover in the range from 10 to 25 per cent. The other plant life form categories had lower relative importance values and included fewer plant species than did the layer of low and dwarf shrubs.

In relatively homogenous vegetation dominated by one or a few plant species, fuel loading and biomass may be predicted according to plant characteristics such as height, cover and stem diameter (Catchpole 1985, Catchpole and Wheeler 1992). Double sampling schemes have also been employed successfully to assess biomass in plant communities containing homogeneous patches of several different vegetation types such as grass, shrubs and bare ground (Catchpole and Catchpole 1993). These approaches were not considered practical at the Stirling Range study site because of the variability in floristic composition and structure of the vegetation. A large number of predictive equations would have had to be developed to cater for the different shrub species that could potentially contribute to the fuel loading at any given location. The fact that significant correlations were established between point intercept density and loading for a range of fuel components indicates the potential of this technique for non-destructive estimation of fuel loading, as well as for estimation of cover and height. However, point intercept sampling is time consuming and requires a large number of samples to give precise fuel loading estimates. Schneider and Bell (1985) investigated the use of the disc-drop technique (see Powell 1974, Bransbury and Tainton 1977) to estimate standing biomass in Western Australian shrublands somewhat similar to those at the Stirling Range, but were unable to establish a strong correlation between disc height and biomass. They attributed the error in estimates of standing biomass primarily to the presence of plants with heavy branching, notably *Banksia* and *Hakea*, which impeded the downward movement of the disc thereby resulting in overestimates of the biomass. Labour intensive fuel sampling techniques would only be justified if precise information about fuel characteristics were required to predict the likely range of fire behaviour at a particular location. In most situations, general models which describe fuel height, loading and cover in relation to vegetation age are probably adequate for making fire behaviour predictions.

The fuel sampling strategy employed for this study sought to characterise the structure and loading of the fuel at a plant community level rather than according to the characteristics of individual plant species. Fuel sampling was weighted towards the vegetation type that was most widespread within the study area (Plots I, J, K, L) but localised vegetation types that were either sparser (Plot C) or denser (Plot N) than average were also sampled. Litter was the most variable component of the fuel, with loading varying by a factor of twofold and cover by a factor of 1.4 between the highest and lowest plot averages. Some of the variation in litter loading and cover was explained by variation in the height of the vegetation (equations 2.2 and 2.3) and it is likely that further variation would be attributable to species-linked characteristics including the size and shape of leaves, the quantity and timing of litter fall, and the propensity of the plant to retain dead foliage. For example, the tall shrubs *Lambertia inermis* and *Dryandra sessilis* have leaves that are much smaller than those of the eucalypts (see Section 3.3, Table 3. 7), and also tend to retain some dead foliage on the plant. Visually, the layer of leaf litter beneath these species of shrubs appeared to be shallower and less continuous than beneath mallee eucalypts of comparable height but this observation could not be tested statistically because plant species composition was not recorded in the individual 1 m^2 quadrats from which litter samples were collected.

The total loading of litter, dead fuel <25 mm and live fuel <6 mm accumulated at an average rate of 0.27 kg m^{-2} per annum over the first five years after fire. Thereafter, the rate of accumulation declined and the total loading tended towards an equilibrium level which was established by the tenth year after fire. Vegetation height and the cover of most live and dead fuel components also approached an equilibrium within ten years following fire. Some fuel components, however, notably the litter and dead fuel <6 mm continued to accumulate over time with the result that the fraction of dead fuel increased in older vegetation. Litter and dead fuel displayed corresponding increases in cover for at least 20 years following fire.

The continuity and cover of the litter bed and the bulk density of the shrub layer are likely to be key factors which affect the spread of fires, at least under marginal burning conditions. Older mallee-heath fuels will tend to be more flammable than younger fuels of equivalent total loading because of the the greater proportion of litter and suspended dead material. The less flammable characteristics of younger fuels are likely to be most apparent under marginal burning conditions when flames spread primarily in the litter and dead fuel component of the dwarf shrubs. This contention is supported by field observations where it has been noted that, under moderate weather conditions (for example, air temperature <25°C, relative humidity >40 per cent, and wind speed <5 m s^{-1} at 10 m height), fuels less than eight years old will not readily burn while fuels older than 15 years may burn with considerable ferocity (McCaw, unpublished data).

Within fuels of a given age, spatial variation in the bulk density of the shrub layer can be substantial due to the characteristics of the vegetation present at particular locations. This was clearly demonstrated by the differences in shrub bulk density between Plots C and I. The minimum bulk density necessary to sustain a spreading fire in mallee-heath is unknown, and is almost certain to vary according to the severity of the burning conditions at the time.

Post-fire fuel accumulation in mallee-heath was adequately described using exponential saturation equations. The goodness of fit of the equation for live fuel would have been adversely affected by the unexpectedly high loadings recorded in the fifth year after fire, the reason for which remains unclear. Rainfall in the year prior to the fifth post-fire measurement was below average making it unlikely that the high live fuel loading was the result of a growth flush caused by favourable seasonal conditions. Exponential saturation equations have been used to model fuel accumulation in a wide range of forests (Jenny *et al*. 1949, Fox *et al*. 1979, O Connell 1987, Fogarty 1993, Burrows 1994, McCaw *et al*. 1996) and shrublands (Burrows and McCaw 1990, Conroy 1993, Marsden-Smedley and Catchpole 1995a). Fuel accumulation at the Stirling Range study site followed a similar pattern to that reported for other shrubland plant communities in the south-west of Western Australia (Delfs *et al.* 1987, Burrows and McCaw 1990), although the equilibrium fine fuel loading in mallee-heath was heavier than the 0.7 kg m^{-2} measured in *Banksia* woodland near Perth by Burrows and McCaw (1990). When comparing equilibrium fuel loadings measured in different studies, the size-class definitions used for the various components of the fuel must be taken into account. Delfs *et al*. (1987) reported total above-ground biomass loading of 1.6-1.8 kg m^{-2} in heathland at Badgingarra but did not separate the various components of the biomass according to size-class or condition. Consequently, their data would tend to over-estimate the quantity of fuel actually consumed during a fire, particularly in older stands of vegetation where a substantial proportion of the live biomass might be comprised of woody stems thicker than 6 mm diameter. Total vegetation cover at Badgingarra was considerably less than in mallee-heath, possibly because of the absence of mallee eucalypts. Specht (1966) examined fuel accumulation after fire in a South Australian mallee community with a shrubby understorey and found that about 0.85 kg m^{-2} of total above-ground biomass had accumulated ten years after fire. The shrubland communities examined by Specht (1966), Delfs *et al*. (1987), Burrows and McCaw (1990) and in this study were characterised by relatively low equilibrium fuel loadings (<2.0 kg m^{-2}) which were attained within about ten years since fire. These plant communities occur in environments which experience a severe moisture deficit during the summer and autumn, and on soils with very low levels of available nutrients. Both factors act to limit the productivity of the plant community and the resulting fuel accumulation (Specht 1969, Hill 1989). In contrast, shrubland communities in more humid environments may continue to accumulate fuels for at least 20 years after fire and attain equilibrium loadings exceeding 3.0 kg m^{-2}, at least on more fertile soils (Specht 1969, Conroy 1993, Marsden-Smedley and Catchpole 1995a).

The equilibrium fine fuel loading in mallee-heath was only about half that measured in 21-year-old fynbos by Van Wilgen (1982). The fynbos community studied by Van Wilgen (1982) differed from mallee-heath in having a much heavier litter accumulation (1.25 kg m^{-2}) and a greater quantity of fuel contributed by tall shrubs (1.08 kg m^{-2}). These loadings are consistent with the relative importance values assigned to the various plant life form categories in fynbos, in particular the predominance of tall shrubs. Kruger (1977) argued that fynbos was distinguished from northern hemisphere shrublands, and from some Australian shrublands, by the presence of a persistent component of herbaceous plants, mostly Restionaceae and Cyperaceae. This herbaceous component comprises the majority of the biomass in young stands, but is progressively overtaken in importance by tall shrubs as the stands mature. The biomass of mature fynbos varies considerably and the 21-year-old community at Jonkershoek is amongst the heaviest recorded (Van Wilgen 1982, 1984). Van Wilgen (1984) developed a stylised fuel model of 15-year-old fynbos for fire danger rating purposes. Component loadings for this model were 0.4 kg m^{-2} of dead fuel <6 mm (1 hour time lag), 0.09 kg m^{-2} of dead fuel 6-25 mm (10 hour time lag), 0.5 kg m^{-2} of live herbaceous fuel and 0.22 kg m^{-2} of live fine woody fuel. Time lag classes distinguish fuel components according to their responsiveness to atmospheric conditions and provide the definition for component loadings in the United States Fire Danger Rating

System (Deeming *et al*. 1978). The combined fine fuel loading for the stylised model is approximately 1.2 kg m^{-2} which is similar to the fine fuel loading in 20-year-old mallee-heath. Possible application of the fynbos fuel model for predicting fire behaviour in mallee-heath is examined in Chapter 5.

The time interval since the last fire affects not only the loading and composition of the fuel, but the maturity of the plant community as a whole. A number of fire sensitive shrub species which store seed in capsules on the mature plant did not flower for the first time until at least seven years after fire, and would take considerably longer to accumulate a substantial store of seed. An interfire period of at least ten years was necessary for all the plants in the sample population of *H. crassifolia* to have flowered for the first time. Gill and Nicholls (1989) reviewed published studies of seed production by fire sensitive plants and concluded that a species is likely to be able to replace itself to pre-fire abundance levels if the interval between succesive fires is at least twice the length of the primary juvenile period of the species concerned. An interval of at least 14 years between fires would be required to satisfy this criterion for the mallee-heath community at the Stirling Range study site, if the plant species with the longest primary juvenile periods were taken into account. Tall shrubs are the most likely of all the plant life form groups in mallee-heath to be disadvantaged by fires at shorter intervals because the majority of these species store seed in capsules on the mature plant. Successive fires at relatively short intervals would tend to eliminate the stratum of tall shrubs, resulting in a plant community comprised of resprouting mallee eucalypts and shrubs <1 m tall. Plants that are capable of resprouting after fire, or which regenerate from seed stored in the soil are less likely to be disadvantaged by short intervals between fires, up to the point where rootstocks become depleted and the store of seed in the soil is exhausted. Fires are unlikely to spread to any substantial extent in mallee-heath less than eight years old unless the burning conditions are severe (McCaw *et al*. 1992). The critical age range during which the composition of mallee-heath plant communities may undergo long term alteration due to fire is likely to be between about eight and 14 years. This is because the fuels are sufficiently continuous to carry extensive fires, but the slower maturing species of tall, fire sensitive shrubs do not yet carry substantial seed stores. The need to exclude both prescribed and unplanned fires from areas of immature vegetation has been recognised as an important fire management objective for mallee-heath communities (Herford *et al*. 1996)

In addition to fire frequency, the intensity and patchiness of fires may also affect the persistence of fire sensitive species at a landscape level. Unburnt patches and areas burnt at very low intensity may provide refuges which allow fire sensitive species to persist in a landscape subject to fires at intervals shorter than that required for seed stores to accumulate. However, a simulation study by Bradstock *et al*. (1996) of the effect of spatial and temporal variation in fire regimes on the population viability of a fire sensitive *Banksia* species in New South Wales heathland indicated that fire patchiness alone cannot be assumed to ensure avoidance of extinction for populations. A sound understanding of the interactions between the frequency, intensity, seasonality and patchiness of fires is fundamental to the management of fire in natural ecosystems, particularly where fire is employed as a management tool. Such issues are beyond the scope of this thesis, but deserve further investigation in mallee-heath communities.

2.7 Conclusions

Mallee-heath vegetation at the Stirling Range is floristically rich, and a large number of shrubs may potentially contribute to the fuel bed. More than half of the plant species recorded in the quadrats were shrubs <1 m tall, and these shrubs contributed the greater proportion of the cover and fuel loading. Fuel accumulation was modelled as a function of time since fire, with the total fuel loading comprised of litter, dead fuel <25 mm and live fuel <6 mm remaining relatively constant after 10 years since fire. The proportions of total loading contributed by litter and dead fuel <6 mm continued to increase up to at least 20 years after fire, as did the cover of these components. Continued increase in the loading and cover of dead fine fuel is consistent with field observations that fires burn more readily in older stands of mallee-heath than in younger stands that have a comparable total fuel loading. Total fuel loading at age 20 years averaged 1.32 kg m^{-2} in the five plots which were typical of the mallee-heath at the study site, while the loading in Plot C was only 0.87 kg m^{-2}. Under moderate burning conditions in spring and autumn about 1.15 kg m^{-2} of fine fuel is likely to be consumed in a fire. This is similar to equilibrium fuel loadings reported for other shrubland plant communities in Western Australia and South Australia, but substantially less than recorded in shrublands in more humid environments. About 20 per cent of the vascular plants recorded in mallee-heath were fire sensitive shrubs with capsule-stored seed. A number of the common shrubs in the >1 m stratum of the vegetation exhibited this post-fire response strategy, some of them having primary juvenile periods of 7 years or longer. Successive fires at intervals of less than about 14 years may disadvantage shrubs with longer juvenile periods by limiting the opportunity for on-plant seed stores to accumulate.

CHAPTER 3

MOISTURE CONTENT OF DEAD AND LIVE FINE FUELS IN MALLEE-HEATH

3.1 Introduction

Fuel moisture content directly affects the ease of ignition and rate of combustion of fuel particles and fuel beds (for example Byram 1959, Pompe and Vines 1966, Gill *et al.* 1978). For this reason, variation in the moisture content of one or more size classes of fuel is taken into account, either directly or indirectly, in most fire danger rating and fire behaviour prediction systems (Nesterov 1949, McArthur 1962, 1966, 1967 & 1977, Deeming *et al*. 1972 & 1977, Sneeuwjagt and Peet 1985, Andrews 1986, Van Wagner 1987, Forestry Canada 1992, Cheney *et al*. 1992, Burrows 1994, Marsden-Smedley and Catchpole 1995b).

Factors determining the moisture content of fine dead fuel particles, and in particular forest litter, have been studied extensively and a number of models have been developed to predict dead fuel moisture content. In a comprehensive review of fuel moisture modelling, Viney (1991) distinguished between models which describe the moisture content of fuels under specific exposure conditions, which he termed vapour exchange models, and models based on the concept of equilibrium moisture content. Amongst those categorised as vapour exchange models, the models of McArthur (1962, 1967 & 1977) and Sneeuwjagt and Peet (1985) are most commonly used for fire danger rating and fire behaviour prediction purposes in Australia. Equilibrium moisture content (EMC) is the moisture content that a fuel particle will attain under given environmental conditions if left for sufficient time. Relationships between temperature, relative humidity and EMC under adsorption and desorption conditions have been established experimentally for wood and a range of other dead fuel particles (Simard 1968, Van Wagner 1972, Anderson *et al*. 1978). A semi-physical formulation of EMC has also been applied to forest fuels by Nelson (1984). Closely linked to EMC is the concept of response time which is the time required for 1 - e^{-1} (approximately 63 per cent) of the change between the initial moisture content of the fuel and EMC to take place (Viney 1991). Response time is closely related to the size of the fuel particle, and is also affected by other characteristics including particle density, surface coating and the extent of weathering (Anderson 1990a).

Live foliage and fine twigs (<6 mm diameter) make up a substantial proportion of the fuel load in many shrubland plant communities. Live fuels typically have much higher moisture contents than dead fuels, and require more extensive pre-heating prior to pyrolisis than is the case for dead fuels. The presence of moisture in the fuel delays the rise to critical ignition temperature (Van Wagner 1967a) and also affects the radiation characteristics of the flames, reducing the extent to which fuels in advance of the flame front are pre-heated (Vines 1981). Live fuels may therefore act as a net heat sink, particularly during the initiating phase of a fire (Tunstall 1991). Suppressive effects of live fuel moisture on fire behaviour may, however, be offset to some degree by flammable terpenes and waxes which promote combustion during the early stages of burning (Vines 1981). Such compounds are common in the foliage of many of the sclerophyllous shrubs and trees occurring in Western Australian shrublands.

Live fuel moisture content has been included as a variable in a number of models developed to predict the behaviour of fires in forests and shrublands, including the oak chaparral model of Lindenmuth and Davis (1973), the conifer crown fire model of Van Wagner (1977a), the gorse and heather model of Thomas (1971) and the oak garrigue model of Trabaud (1979). Seasonal variation in the foliage moisture content of trees (eg. Jameson 1966, Van Wagner 1967b, Philpot and Mutch 1971, Chrosciewicz 1986) and shrubs (Dell and Philpot 1965, Pirsko and Green 1967, Green 1981, Weise *et al*. 1991) has been proposed as having an important influence on the relative flammability of some plant communities. Valette *et al*. (1994) correlated the moisture content of growing tips from *Erica* shrubs with an ignition delay index to provide a measure of changes in the seasonal flammability of shrublands in mediterranean France. High foliage moisture content has also been proposed as one of the reasons that patches of evergreen Afromontane forest burn less often than surrounding fynbos shrublands in southern Africa (Van Wilgen *et al*. 1990).

Patterns of variation in the moisture content of live and dead fine fuels and relationships between fuel moisture content and environmental conditions have not previously been investigated in mallee-heath. The objectives of the studies described in this chapter were:

- to describe the pattern of variation in fuel moisture content for the litter layer and for elevated dead fuel components, and to determine whether some existing models for predicting dead fuel moisture content could be applied to mallee-heath; and

- to measure live foliage moisture content for several common mallee-heath shrubs in order to obtain representative values for input to existing fire spread models, and to determine whether there is a seasonal pattern of variation in live fuel moisture content.

3.2 Dead fine fuels

3.2.1 Experimental Methods

Dead fuel moisture content data were collected in 20-year-old mallee heath at the Stirling Range study site (Section 2.3), and in a planted mallee stand at the Perup field research station about 70 km east of Manjimup (34° 15'S, 116° 09'E). The vegetation at Perup was of similar height and canopy cover to the mallee-heath at the Stirling Range. Studies were undertaken at Perup because the field station had the necessary facilities to support an extended run of fuel moisture sampling over several days. Diurnal variation in the moisture content of litter and elevated dead fuel was examined at both sites. Artificial litter baskets and leaf bunches were used in order to minimise the variation due to sampling error, which can be considerable for randomly collected samples of litter and elevated dead fuel. Litter baskets were prepared using rectangular black plastic seedling trays (0.25 m x 0.35 m) from which the original bases had been removed and replaced with plastic gutterguard (10 mm mesh). This arrangement permitted contact between the litter and the soil, allowing the baskets to approximate the behaviour of litter *in situ*. The dimensions of the mesh were sufficient to prevent individual leaves being lost from the tray. Leaf litter was collected from beneath mallee-clumps and placed within baskets to form a layer 5-10 mm thick. Five replicate litter baskets were prepared in this manner. Baskets used at the Stirling Range contained 50-60 g of litter while those used at Perup contained 20-30 g of litter. Leaf bunches consisted of about five dead *D. drummondii* leaves held together by a short piece of wire wrapped around the leaf petioles. Bunches weighed 16-20 g and were loosely packed so as to be representative of the elevated dead fuel as it occurred within undisturbed shrubs. Litter baskets were placed on the ground and leaf bunches were supended from wire pegs (Plates 5 & 6).

Data were collected at the Stirling Range over seven days which comprised four separate runs of the experiment: 20, 21 and 22 November 1990; 24 January 1991; 21 February 1991; and 25 and 26 February 1992. Litter baskets and leaf bunches were

Plate 5 Litter basket placed on ground in mottled shade conditions beneath mallee clump

Plate 6 Bundle of dead *D. drummondii* leaves suspended on a wire peg to simulate elevated dead fuel in undisturbed shrubs.

weighed at hourly intervals between dawn (0600 hours Western Standard Time) and sunset (2100 hours and 2000 hours respectively) on 21 January 1991 and 25 February 1992. At other times, measurements extended over periods from three to ten hours and intervals between weighings ranged from one to three hours. Details of environmental conditions during each run of the experiment are provided in Table 3.1. Litter baskets and leaf bunches were located in an open area of mallee-heath that experienced full sun conditions throughout most of the day except when sun angles were low during the early morning and late afternoon. Litter baskets and leaf bunches were weighed to the nearest 0.1 g with an electronic balance located in a caravan adjacent to the site. At the completion of each experimental run, baskets and bunches were oven dried in the laboratory at 105°C for 18 hours and periodic measurements of weight were converted to moisture content expressed as a percentage of oven dry weight. On 21 January 1991 and 25 February 1992, litter and elevated dead *D. drummondii* leaves were collected at 0800, 1200, 1500 and 2000 or 2100 hours for determination of oven dry moisture content as a comparison with the weighed litter baskets and leaf bunches. At each sampling time, five samples (20-30 g each) were collected from the litter bed near the baskets and three samples were collected from dead foliage retained within intact *D. drummondii* shrubs. Litter and leaves were also sampled in this manner at 1500 hours on 26 February 1992.

Air temperature and relative humidity were recorded during each run using a Lambrecht thermohygrograph in a standard instrument shelter. Solar radiation and wind speed were recorded at 2 m height above ground using a UNIDATA automatic weather station and data logger located in the open at the site. Fuel-level temperature was measured on 20-21 November 1990, 21 January 1991, and 25-26 February 1992. Chromel-alumel thermocouples (20 gauge) were inserted between pairs of dead *E. pachyloma* leaves held together with small sections of transparent tape. Care was taken to ensure that thermocouples were in contact with the inner face of the resulting leaf envelope and were shielded from direct radiation. Thermocouples were connected to a Leeds and Northrup multi-channel data logger which recorded the temperature of each probe sequentially every two minutes. Pairs of thermocouples were placed at 0.5 m above ground in a mallee clump which provided mottled shade, and on the surface of the litter layer in an open area exposed to full sunlight.

At Perup, the moisture content of litter baskets and leaf bunches was monitored over a three day period from 1100 hours on 15 April to 1100 hours on 18 April 1996. Baskets and bunches were weighed at hourly intervals, except between 0100 and 0500 hours on 18 April. Three replicate samples were also collected from the litter layer at hourly intervals for moisture content determination by oven drying. Experimental procedures were the same as those employed at the Stirling Range, except that the litter baskets and leaf bunches were placed beneath a partial canopy of mallee eucalypts that provided mottled shade. Air temperature, relative humidity, solar radiation and wind speed at 2 m height were measured using an ENVIRONDATA portable electronic weather station.

An additional set of dead fuel moisture data was available from samples collected in conjunction with experimental fires. At the time of each fire, five replicate samples were collected from: the shallow litter layer (depth <10 mm) on the ground beneath the shrub layer; the deep litter layer (depth 10-30 mm) beneath clumps of mallee eucalpts, generally *E. pachyloma*; and from the elevated dead foliage on *D. drummondii* shrubs. Individual samples were sealed in air-tight tins and subsequently oven dried at 105°C for 18 hours to determine moisture content. Further details of sampling methodology are provided in Section 4.3.3. Dates and times of sample collection in conjunction with experimental fires are shown in Table 4.1 in Chapter 4.

3.2.2 Models used to predict dead fuel moisture content

Four moisture prediction models were evaluated to determine their applicability to mallee-heath. Three of the models are empirically derived and apply to litter fuel in open eucalypt forest or to cured grassland. These models are commonly used in Australia to predict fuel moisture content for fire danger rating and fire behaviour prediction, and so their applicability to mallee-heath is a question of some practical relevance. The fourth model is based on a semi-physical formulation of EMC used in association with a time-step procedure to account for the response time of the fuel. Principal features of each model are described below:

Forest Fire Behaviour Tables (FFBT) for Western Australia

The FFBT (Sneeuwjagt and Peet 1985) provide a model to predict the Surface Moisture Content (SMC) which is defined as the moisture content of the upper 5-10 mm of the litter bed in open forest of jarrah (*Eucalyptus marginata*). The SMC is calculated using a book-keeping procedure which predicts values at 0800 hours (assumed maximum) and 1500 hours (assumed minimum). The FFBT were not intended to model fuel moisture content throughout the diurnal cycle (R. Sneeuwjagt[1], pers. comm.), but a simple nomogram is provided to predict SMC at other times between 0800 hours

[1].R. Sneeuwjagt, Fire Operations Manager, Department of Conservation and Land Management, Perth, Western Australia

and 1700 hours. Basic inputs used to calculate the SMC for the day are maximum air temperature, minimum relative humidity, and rainfall in the 24 hour period to 0800 hours or alternatively the overnight humidity count determined from a thermohygrograph chart. Further details of the calculation procedure are provided in Sneeuwjagt and Peet (1985). Viney (1991) has derived a mathematical expression for determination of the ovenight humidity count. Calculations may be initialised with a moisture content measured in the field, or by setting the 0800 hour moisture content at 60 per cent on the first day following 10 mm of rain.

Control burning in eucalypt forests (CBEF) model of McArthur (1962)

The CBEF model uses screen level air temperature and relative humidity to predict the moisture content of the surface layer of leaves in a eucalypt litter bed receiving about 25 per cent of full sunlight (McArthur 1962). Separate relationships are provided for fuels under desorption conditions (0600-1200 hours) and adsorption conditions (1200 hours onwards). Desorptions conditions are also considered to apply continuously for two days following rainfall of 12.5 mm or more. McArthur's original graphs have subsequently been expressed in mathematical form with metric units by Viney (1991):

Desorption conditions $$M = 0.113\ RH - 0.218\ T + 12.5 \qquad (3.1)$$

Adsorption conditions $$M = 0.132\ RH - 0.168\ T + 6.8 \qquad (3.2)$$

where M is the per cent moisture content of the fuel and RH and T are relative humidity and air temperature respectively.

Grassland Fire Danger Meter (GFDM) model of McArthur (1977)

The Mark V Grassland Fire Danger Meter of McArthur (1977) provides a simple model to predict the moisture content of grass fuel based on screen level air temperature and relative humidity. A basic fuel moisture content is calculated for fully cured grass, and may be corrected if grass curing is incomplete. The model is presented in a slide rule format on the original meter, and has also been expressed in the form of an equation by Noble *et al.* (1980):

$$M = (97.7 + 4.06\ RH)/(T + 6.0) - 0.00854\ RH \qquad (3.3)$$

where M is the moisture content of fully cured grass and T and RH are as defined previously. McCaw and Catchpole (1997) have drawn attention to a discrepancy between predictions from the original model presented on the slide rule and the equation fitted by Noble *et al*. (1980). This discrepancy may be as large as 3 per cent moisture content when T is below 20°C and RH is above 40 per cent, but reduces as conditions become warmer and drier. Regrettably, the fate of the original data from which the model was derived is unknown and it is not possible to determine how well either function describes the relationship between M, T and RH. The equation of Noble *et al*. (1980) has received wide acceptance (for example Gill *et al*. 1987, Viney and Hatton 1989, Pook 1993, Cheney *et al*. 1993), presumably because it is readily programmed to calculate fuel moisture content from sets of weather data. For the purpose of this study, fuel moisture contents were calculated using the equation as this is now the more widely used version of the model.

EMC model of Nelson (1984)

Nelson (1984) proposed a two parameter model based on an exponential relationship between Gibbs free energy change, ΔG, and the equilibrium moisture content, M_e, of a fuel particle:

$$M_e = a + b \log \Delta G = a + b \log \{- (RT/m) \log H\} \qquad (3.4)$$

where a and b are regression constants, R is the universal gas constant, T is the temperature (in Kelvin), m is the molecular weight of water and H is the fractional relative humidity. Constants a and b vary according to fuel type, and whether the fuel is adsorbing or desorbing (Nelson 1984). Anderson (1990b) modelled a and b as quadratic functions of surface temperature for a range of fuel particles and suggested that the fuels examined could be conveniently grouped into four categories based on their EMC characteristics. The EMC data for fir and spruce needles in Anderson’s study most closely matched those obtained for *Eucalyptus obliqua* and *Eucalyptus radiata* leaves by King and Linton (1963). The two eucalypt species remained within 2 per cent of the EMC determined for fir and spruce up to a relative humidity of 70 per cent. At higher humidities, the eucalypt litter exhibited higher EMC’s than did fir and spruce needles.

Byram (1963) showed that the change in moisture content of a fuel particle over time can be approximated by:

$$dM/dt = -(M - M_e)/r \qquad (3.5)$$

where M is the moisture content of the fuel particle at time t, M_e is the equilibrium moisture content and r is the response time of the fuel element. Using an iterative process, this relationship can be utilised to relate M to M_e over a diurnal cycle (Van Wagner 1977b, Nelson 1991). The average moisture content M of a fuel particle over a small time step, say 1 hour, is then described by the following equation:

$$M = (M_0 r + M_e dt)/(r + dt) \qquad (3.6)$$

3.2.3 Data analysis

FFBT, CBEF and GFDM models

Predictions from the three empirical models (FFBT, CBEF, GFDM) were compared with fuel moisture data collected at the Stirling Range study site. SMC values were calculated for the 18 experimental fire days and for 20 and 22 November 1990; incomplete overnight humidity data prevented calculation of an SMC for the other five days on which fuel moisture content was measured in the field. The SMC was initialised at 60 per cent by backdating to the last rainfall exceeding 10 mm, or at 3 per cent on a day when the maximum air temperatures exceeded 35°C following a period of more than ten days without rain. Predictions were run for at least seven days prior to the day for which the SMC and the measured moisture content were compared. Examination of the data showed that the SMC was relatively insensitive to the initialisation value provided that calculations were run for this period. Measured moisture contents were compared with the SMC at 1500 hours, or the time of sample collection if this differed from 1500 hours. Where necessary, SMC values for the time of sample collection were interpolated using the nomogram provided by Sneeuwjagt and Peet (1985). Equations (3.1) and (3.2) were used to predict eucalypt litter moisture contents for the 18 experimental fires and for the other 54 observation times shown in Table 3.1. Moisture contents for cured grass were predicted for the same data set using equation (3.3).

Nelson's diurnal EMC model

The first stage in the evaluation of Nelson's (1991) model was to obtain estimates of the response time, r, for litter samples, litter baskets and leaf bunches. This was done using the data collected at Perup which comprised sequential hourly observations over three days and nights, thereby giving a good estimate of the lag between M and M_e over the diurnal cycle. Hourly values of M_e were calculated from equation (3.4) using values for R and m provided by Nelson (1984). The fuel specific constants a and b were calculated using the method of Anderson (1990b) with coefficients for weathered Douglas Fir (*Pseudotsuga menziesii*) which he found to have a similar EMC response to eucalypt litter. Fuel level temperature was represented by the temperature of thermocouples placed on the ground (for litter baskets) or suspended above the ground (for leaf bunches) in dappled shade. Fuel level relative humidity was estimated from screen level humidity recorded by the ENVIRONDATA weather station using the relationship provided by Nelson (1991) which assumes that the vapour pressure at fuel level is the same as that of the ambient air.

Moisture contents were predicted at hourly intervals using equation (3.6) with nominal response times of 1, 2 and 3 hours for litter and 1, 2, 3 and 4 hours for elevated dead fuel. Predictions were initialised using the measured moisture contents of litter baskets and leaf bunches at the commencement of the experimental run to avoid any error resulting from initial differences between M_e and M. Measured moisture contents for litter samples, litter baskets and leaf bunches were then compared with corresponding predictions for each nominal value of r. Error statistics were examined to determine which value of r resulted in the best fit to the measured moisture content data; statistics examined were MAE, RMSE and mean bias (MB) calculated as $\sum_i (y - y)/n$, where y and y are the observed and predicted values respectively and n is the number of observations.

In the second stage of the evaluation, predictions made using Nelson's (1991) model with values of r obtained using the procedure described above were compared with the moisture contents of litter baskets and leaf bunches measured over five days of sampling at the Stirling Range study site (Table 3.1). The days included in this data set were those for which thermocouple measurements of fuel level temperature were available. Periodic values of M_e and M were predicted using the same procedure as employed for the Perup data, the only difference being the variable length of the time steps on 20-21 November 1990 and 26 February 1992. Fuel level temperatures for exposed litter on the ground were also predicted from the relationship of Byram and Jemison (1943), and subsequently used to calculate values of M_e and M. Byram and Jemison's equation has air temperature, solar radiation and wind speed as inputs. Air temperatures were taken from the thermohygrograph chart, and solar radiation and wind speed from the UNIDATA weather station, with the latter two variables averaged over the 30 minutes prior to the time of the prediction. Fuel level wind speed was approximated by 0.1 U_2, which equates to the mean wind speed at 0.5 m above ground in mallee-heath estimated from the experimentally derived wind profiles (Appendix C). Fuel level relative humidity was determined from predicted fuel level temperature using Nelson's (1991) relationship.

3.2.4 Results

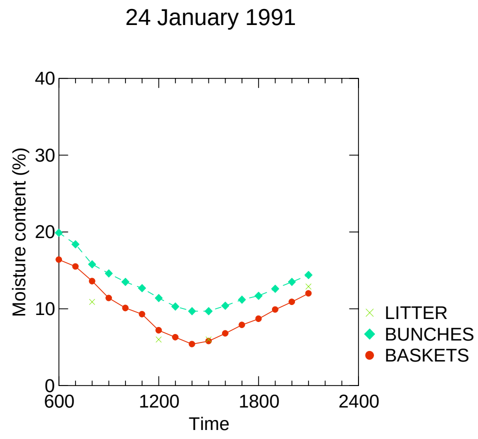
Diurnal variation in fuel moisture at the Stirling Range study site

Fuel moisture studies at the Stirling Range were undertaken in spring and summer during mild to warm weather conditions (Table 3.1). Substantial rainfall was recorded on 15 and 16 November (17.4 and 3.8 mm respectively) prior to the commencement of the first run of the experiment. The experimental run in January 1991 commenced following 6 rain free days, and that in February 1992 after 16 rain free days. No rainfall was recorded during any of the experimental runs, but heavy dew was present on the litter and elevated fuels at 0600 hours on the morning of 25 February 1992.

TABLE 3.1

Date, duration and number (n) of measurements made with litter baskets and leaf bunches at the Stirling Range study site. Minimum-maximum values of air temperature (*T*), relative humidity (*RH*), dew point (*DP*) and moisture content for litter baskets and leaf bunches during each measurement period are shown. Asterisks indicate the days on which fuel level temperatures were measured with thermocouples.

Date d/m/y	Period of measurement	n	*T* (°C)	*RH* (%)	*DP* (°C)	Moisture content (%) Baskets	Moisture content (%) Bunches
20/11/90	1200 - 1930	5*	13 - 20	42 - 85	7 - 11	9 - 13	12 - 14
21/11/90	0615 - 1600	6*	13 - 19	52 - 78	9 - 12	9 - 23	14 - 23
22/11/90	1200 - 1600	3	18 - 19	52 - 55	9	8	14
24/01/91	0600 - 2100	16*	13 - 26	35 - 97	9 - 15	5 - 16	10 - 20
21/02/91	0900 - 1700	4	19 - 20	74 - 92	15 - 17	11 - 13	16 - 27
25/02/92	0615 - 2000	15*	16 - 26	31 - 83	8 - 15	5 - 31	10 - 42
26/02/92	0700 - 1500	5*	17 - 31	16 - 72	2 - 12	4 - 21	5 - 17



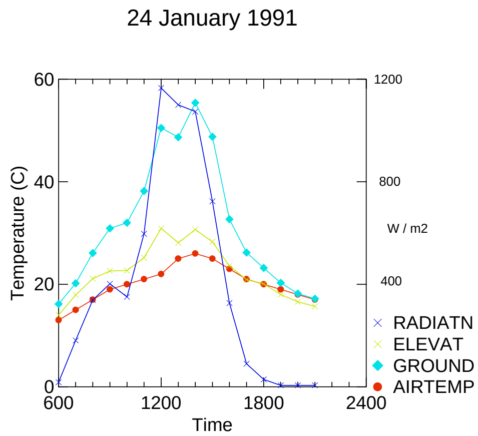
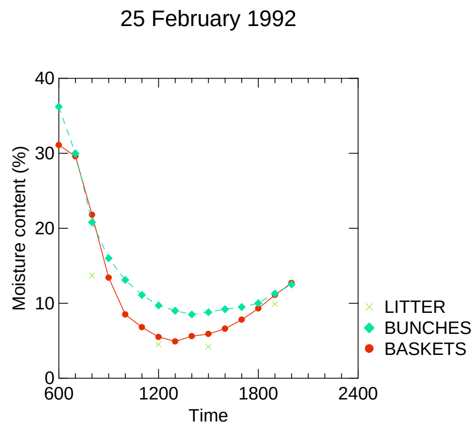


Figure 3.1 (a) Moisture content of litter baskets, leaf bunches and litter samples and (b) screen level air temperature, and leaf temperatures measured on the ground and at 0.5 m elevation in a mallee clump on 24 January 1991. Solar radiation recorded at 2 m height in the open is shown (continuous line).

Trends in the moisture content of litter baskets and leaf bunches for the two longest experimental runs are shown in Figures 3.1 and 3.2. Standard errors (not shown) for the five replicates were always less than 10 per cent, and often less than 5 per cent of the mean. Litter baskets consistently had lower moisture contents than did leaf bunches, particularly during the late morning and early afternoon when baskets were up to 4 per cent drier than bunches. This same pattern was observed on the other five days of the experiment. On 25 February 1992, samples affected by dew dried rapidly during the morning and attained similar minimum moisture contents to those recorded on 24 January 1991. The lowest moisture contents recorded during the study were 4 per cent for litter baskets and 5 per cent for leaf bunches at 1500 hours on 26 February 1992.



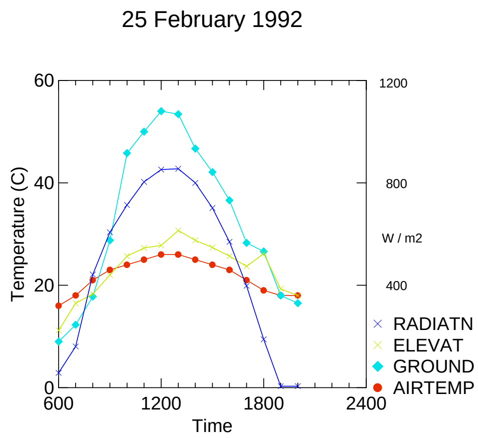


Figure 3.2 (a) Moisture content of litter baskets, leaf bunches and litter samples and (b) screen level air temperature, and leaf temperatures measured on the ground and at 0.5 m elevation in a mallee clump on 25 February 1992. Solar radiation recorded at 2 m height in the open is shown (continuous line).

The mean moisture content of samples taken directly from the litter bed was within 2 per cent of the moisture content of the litter baskets on seven out of nine occasions (Figures 3.1 and 3.2). On the other two occasions, both at 0800 hours, the litter samples were considerably drier (3 and 8 per cent) than the baskets. This was attributed to overnight condensation of moisture on the plastic trays which were in exposed conditions. Samples taken from the litter bed tended to be slightly drier than the baskets but the difference was not significant in a paired sample t test ($P = 0.09$). Leaves harvested from shrubs had moisture contents within 2 per cent of leaf bunches on six of the eight occasions when samples were collected, and the difference between the two was not significant ($P = 0.264$) in a paired sample t test. Due to the possibility of serial correlation in the data, repeated measures analysis of variance would need to be undertaken before accepting these findings conclusively.

Thermocouples attached to elevated leaves were up to 5°C hotter than the ambient air temperatures during the late morning and early afternoon on the 24 January 1991 and 25 February 1992, but otherwise closely matched the ambient temperature. Leaves on the ground exposed to full sunlight typically experienced temperatures that were 20-30°C above ambient between 1000 and 1500 hours, with the highest leaf temperature recorded (55°C) at 1400 hours on 24 January 1991. Leaf temperatures reflected the diurnal pattern of solar radiation, and were generally close to the ambient air temperature before sunrise and after sunset. Leaf temperatures were up to 7°C below air temperatures before 0800 hours on 25 February 1992, probably because of dew on the leaves.

Comparison with moisture contents predicted by the FFBT, CBEF and GFDM

Samples of shallow and deep litter collected at the time of experimental fires were consistently drier than the SMC calculated from antecedent weather conditions by as much as a factor of three (Figure 3.3). Shallow litter was mostly below 10 per cent and deep litter mostly below 14 per cent moisture content, whereas corresponding SMC values were between 14 and 28 per cent. The relationship between the SMC and the moisture content of elevated dead fuel (not shown) was similar to that for litter.

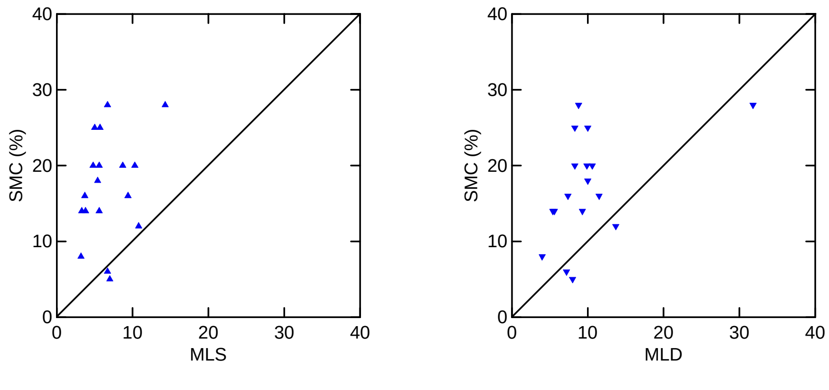


Figure 3.3 Comparison of the jarrah Surface Moisture Content (SMC) calculated from antecedent weather data with measured moisture contents for shallow litter (M_{ls}) and deep litter (M_{ld}) in mallee-heath.

Moisture contents calculated with the CBEF model matched reasonably well with the samples of deep litter collected during experimental fires, except for one outlier that was affected by light rain (2 mm) on the day prior to sampling (Figure 3.4). Shallow litter moisture content exhibited a wider scatter about the line of agreement, althought the overall trend was still consistent with predictions from the model. Litter basket moisture contents were significantly correlated with predictions from the CBEF model (r = 0.700, $P < 0.001$). Up to a predicted moisture content of about 15 per cent, basket moisture contents were consistently 2 to 3 per cent lower than predicted by the CBEF. Above this level there were a number of outliers evident in the data set, all of which corresponded to desorption conditions. Examination of the data showed that these were mostly observations from the morning of 25 February 1992 when samples were initially affected by dew. This appears to have induced a lag in moisture content that was not accounted for in predictions from the CBEF model.

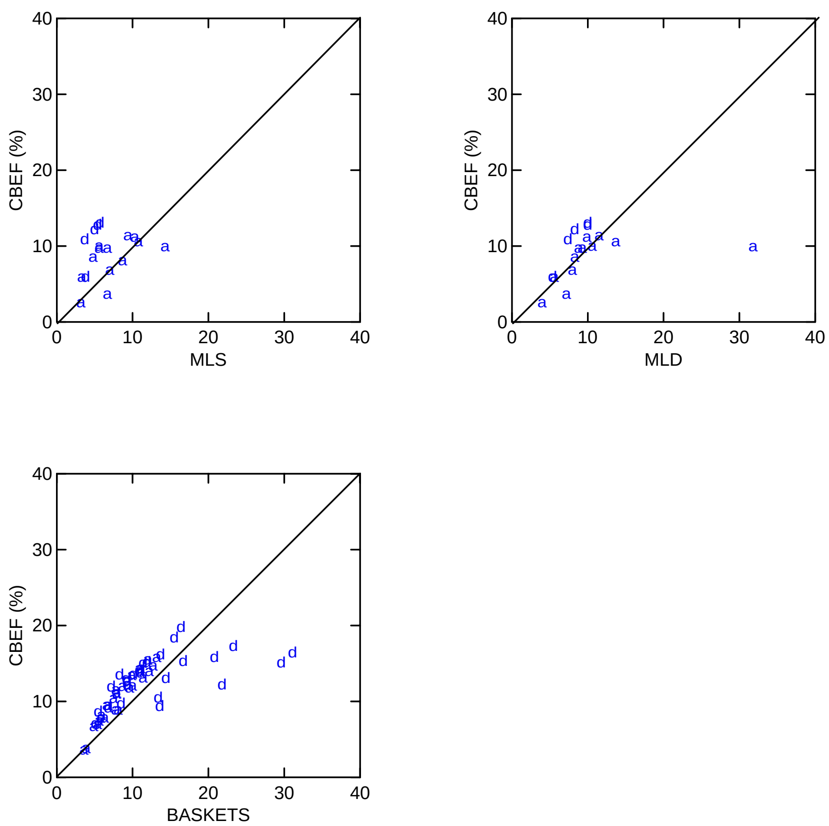


Figure 3.4 Comparison of the moisture content predicted for eucalypt litter by McArthur's Control Burning in Eucalypt Forests (CBEF) model with measured moisture contents for shallow litter (M_{ls}), deep litter (M_{ld}) and litter baskets in mallee-heath. Points labelled d and a indicate samples collected during desorption and adsorption conditions respectively.

The overall trend in the moisture content of elevated dead fuel was consistent with predictions from the CBEF model, although the scatter about the line of agreement was relatively wide (Figure 3.5). Leaf bunch moisture contents were also correlated with predictions from the CBEF model ($r = 0.708$, $P < 0.001$) and there was good agreement between observed and predicted values up to a moisture content of about 18 per cent. At higher moisture contents, the trend was similar to that observed for litter baskets with a number of outliers having considerably higher moisture contents than predicted by the model. Again, the outliers were mostly from the morning of 25 February 1992.

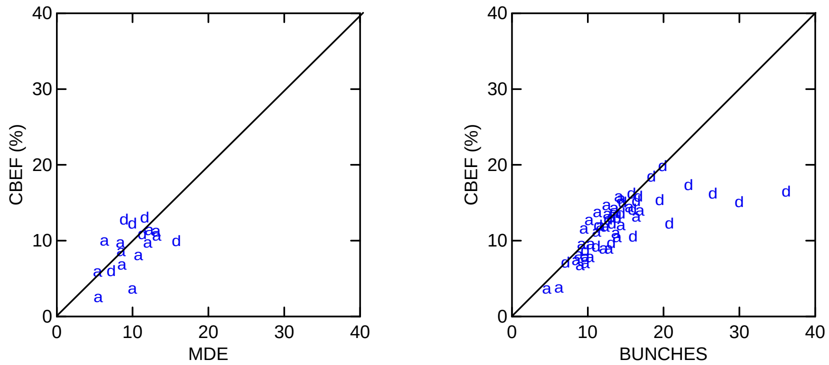


Figure 3.5 Comparison of the moisture content predicted for eucalypt litter by McArthur's Control Burning in Eucalypt Forests (CBEF) model with measured moisture contents for elevated dead fuel (M_{de}), and leaf bunches in mallee-heath. Points labelled d and a indicate samples collected during desorption and adsorption conditions respectively.

Moisture contents predicted for cured grass by the GFDM matched closely with M_{ld} values for experimental fires, with the exception of the single rain-affected outlier previously discussed (Figure 3.6). M_{ls} samples tended to be drier than predicted for grass. Litter baskets were also consistently drier than grass under adsorption conditions, but exhibited considerable variability under desorption conditions. Basket moisture contents were significantly correlated with predictions from the GFDM ($r = 0.621$, $P < 0.001$). In the case of elevated dead fuels (M_{de} and bunches) predictions were evenly distributed but widely scattered either side of the line of agreement (Figure 3.7), and the correlation with predicted moisture contents was poorer ($r = 0.597$, $P < 0.001$) than for the litter baskets.

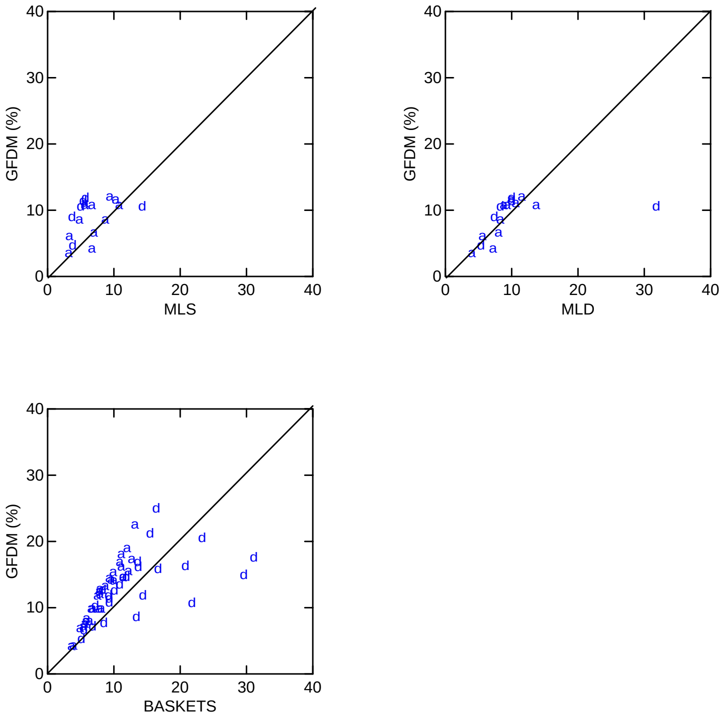


Figure 3.6 Comparison of moisture contents predicted for cured grass by McArthur's Mark V Grassland Fire Danger Meter (GFDM) with measured moisture contents for shallow litter (M_{ls}), deep litter (M_{ld}) and litter baskets in mallee-heath. Points labelled d and a indicate samples collected during desorption and adsorption conditions respectively.

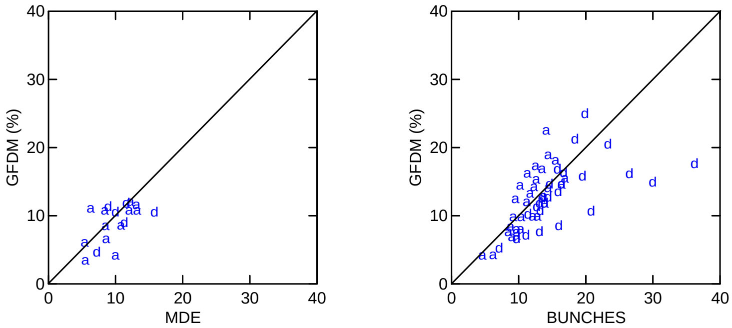


Figure 3.7 Comparison of moisture contents predicted for cured grass by the GFDM with measured moisture contents for elevated dead fuel (M_{de}), and leaf bunches in mallee-heath. Points labelled d and a indicate samples collected during desorption and adsorption conditions respectively.

Comparison with moisture contents predicted using Nelson's diurnal EMC model

Fuel moisture sampling at Perup commenced on the twelfth day following rain and no rainfall was recorded within the 72 hour period over which the sampling extended. Daytime conditions were sunny and mild with maximum temperatures between 22 and 26°C while overnight temperatures fell to between 10 and 15°C (Table 3.2). Conditions became progressively warmer and drier over the three day period, and were notably mild on the third night (18 April) when the air temperature remained constant at 16°C and relative humidity at 46-48% between 0100 and 0500 hours. Dew points were lower and less variable at Perup than during the moisture sampling undertaken at the Stirling Range study site.

TABLE 3.2

Date, duration and number (n) of measurements for litter, litter baskets and leaf bunches at Perup. Minimum-maximum values of air temperature (*T*), relative humidity (*RH*), and dew point (*DP*) are shown.

Date d/m/y	Period of measurement	n	*T* (°C)	*RH* (%)	*DP* (°C)
15/04/96	1100 - 2400	14	11 - 22	42 - 78	7 - 9
16/04/96	0100 - 2400	24	10 - 24	33 - 95	7 - 8
17/04/96	0100 - 2400	24	10 - 26	28 - 72	4 - 6
18/04/96	0100 - 1100	11	16 - 25	49 - 32	5 - 8

Fuels became progressively drier over the three day period of the experiment (Figure 3.8). Maximum moisture contents were similar for the three fuel types, and declined from 22 per cent on the first night to 10-11 per cent on the third night. Daytime minimum moisture contents were 1-2 per cent lower for litter samples than for litter baskets, and both litter fuels attained lower moisture contents than did the leaf bunches. Moisture contents at 0600 hours on 18 April were the same as at 2400 hours on 17 April. Air temperature and relative humidity remained constant during this period it is likely that fuel moisture varied little, if at all.

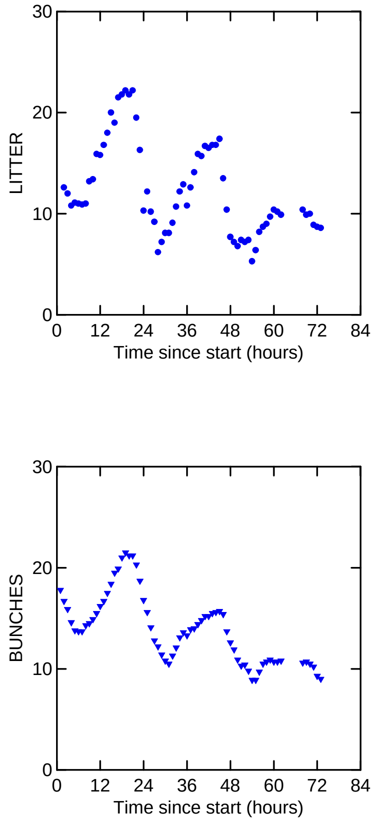


Figure 3.8 Trends in the moisture content of litter, litter baskets and leaf bunches at Perup over three days, starting at 1100 hours on 15 April 1996. Standard errors for the three different types of fuel were mostly less than 5 per cent and always less than 10 per cent of the sample mean.

Tables 3.3 and 3.4 show error and bias statistics for moisture content predictions with varying response times for the Perup data. Predictions for litter baskets had smaller errors than did predictions for litter samples, although litter predictions were slightly less biased. A nominal response time of 1 hour resulted in the best fit between predicted and observed moisture content for litter samples. For litter baskets, there was little difference in MAE, RMSE or MB between response times of 1 and 2 hours. Observed moisture contents for litter and baskets are plotted against predicted values for a response time of 1 hour in Figure 3.9. Predictions were evenly scattered about the line of agreement at moisture contents below 15 per cent, but the model tended to overpredict at higher moisture contents. Overpredictions occurred predominantly during adsorption conditions.

TABLE 3.3

Error statistics for predictions of litter and litter basket moisture content at Perup. Predictions were made using Nelson's diurnal EMC model with nominal response times of 0, 1, 2 and 3 hours. The model was parameterised for fuel temperature measured on the ground in mottled shade.

Fuel type	*r*	MAE	RMSE	MB
Litter (n = 67)	0	1.65	2.04	0.64
	1	1.53	1.85	0.48
	2	1.66	2.14	0.45
	3	1.95	2.48	0.40
Baskets (n = 68)	0	1.43	1.91	0.74
	1	1.02	1.42	0.55
	2	0.97	1.50	0.53
	3	1.20	1.77	0.48

TABLE 3.4

Error statistics for predictions of leaf bunch moisture content at Perup (n = 68). Predictions were made using Nelson's diurnal EMC model with nominal response times of 0, 1, 2, 3 and 4 hours. The model was parameterised for screen level air temperature and fuel temperature measured at 0.5 m above ground beneath a mallee clump.

Exposure	*r*	MAE	RMSE	MB
Screen	0	1.69	2.24	1.24
	1	1.39	1.73	1.04
	2	1.32	1.57	0.96
	3	1.24	1.53	0.80
	4	1.33	1.62	0.73
In mallee clump	0	2.82	3.39	2.80
	1	2.60	2.90	2.60
	2	2.52	2.78	2.52
	3	2.35	2.69	2.35
	4	2.28	2.71	2.28

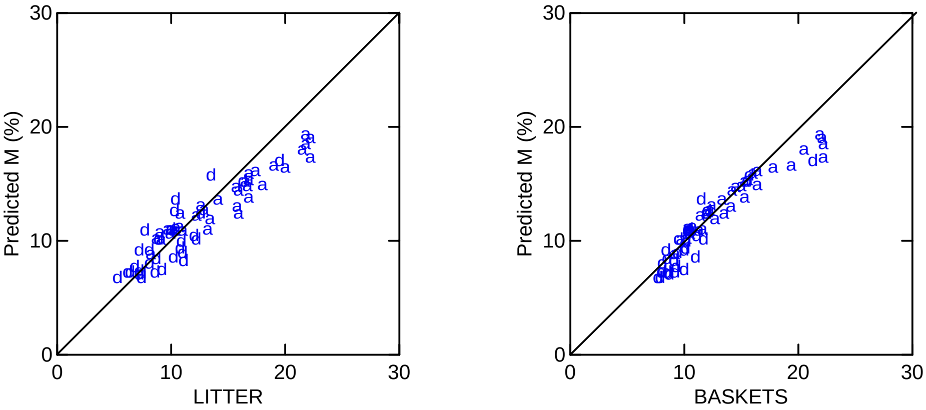


Figure 3.9 Moisture content of litter and litter baskets plotted against predicted moisture contents from Nelson's model with a response time of 1 hour. Symbols d and a indicate samples collected during desoprtion and adsorption conditions respectively.

Moisture contents predicted from screen level conditions fitted the leaf bunch data considerably better than did predictions based on fuel temperatures measured at 0.5 m above ground (Table 3.4). A response time of 3 hours gave the best fit to the screen level predictions, although a tendency towards underprediction during desorption conditions and overprediction during adsorption conditions was evident (Figure 3.10). Predictions based on fuel temperatures measured at 0.5 m were consistently drier than observed moisture contents and there was little difference in error statistics between response times of 3 and 4 hours (Figure 3.10).

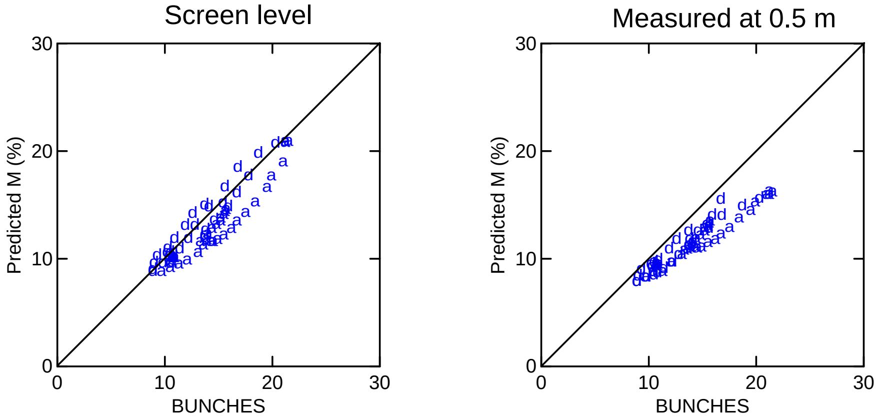


Figure 3.10 Moisture content of leaf bunches plotted against predictions from Nelson's model based on screen level conditions, and the measured temperature of elevated leaves. Response time is 3 hours. Points are labelled as in Figure 3.8.

The next step in the evaluation of Nelson's model was to predict the moisture content of litter baskets and leaf bunches on the five days for which fuel level temperatures were measured at the Stirling Range. On the basis of results from Perup, response times of 1 hour for litter baskets and 3 hours for leaf bunches were applied. Moisture contents predicted for litter baskets are shown in Figure 3.11. Predictions based on measured fuel temperature provided a good fit to the litter basket data over a range of moisture contents from 4-31 per cent. Prediction errors were slightly larger than those for litter baskets at Perup and the bias was negative, indicating a tendency towards overprediction (Table 3.5). The fit to the basket data was slightly poorer when moisture content predictions were based on fuel temperatures calculated using Byram and Jemison's equation. The difference between moisture content predictions based on measured and predicted fuel temperature was greatest when fuels were damp (>20 per cent moisture content), presumably because the cooling effect of surface moisture on the fuel was not accounted for by Byram and Jemison's equation. In drier fuels, moisture content predictions based on predicted fuel temperature agreed reasonably well with basket data. Errors for predictions based on temperatures derived using Byram and Jemison's equation were about a third larger than those for predictions based on measured fuel temperature. Either formulation of Nelson's model was substantially superior to the CBEF or GFDM for predicting the moisture content of litter baskets (Table 3.5). Both the CBEF and GFDM exhibited larger errors and a strong tendency to towards overprediction.

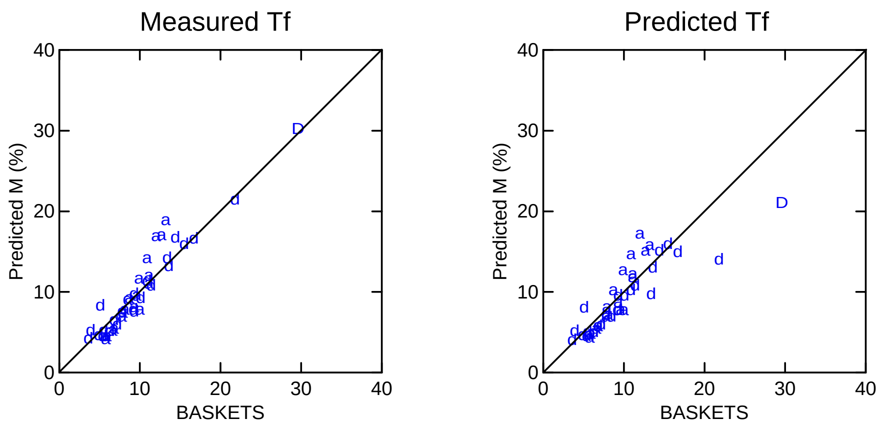


Figure 3.11 Moisture content of litter baskets plotted against predictions from Nelson's model based on (a) measured fuel temperature and (b) fuel temperature predicted using the equation of Byram and Jemison (1943). The nominal response time of the fuel is 1 hour. In both cases, fuel level relative humidity was predicted from screen level measurements using the relationship of Nelson (1991). Symbols d and a indicate samples collected during desoprtion and adsorption conditions respectively, and D indicates a sample affected by dew.

TABLE 3.5

Error statistics for predictions of litter basket moisture content from the CBEF, GFDM and Nelson's model over five days of sampling at the Stirling Range (n = 43). Predictions from Nelson's diurnal EMC are for a response time of 1 hour and relate to fuel temperature (T_f) on the ground in exposed conditions.

Model	MAE	RMSE	MB
Nelson EMC			
measured T_f	1.24	1.80	-0.31
predicted T_f	1.68	2.45	0.40
CBEF	3.16	3.93	-1.51
GFDM	3.88	4.89	-1.96

When predictions from Nelson's model with a 3 hour response time were compared with the leaf bunch data a consistent tendency towards overprediction was apparent (Figure 3.12). Reducing the response time to 2 hours substantially reduced the bias and error in predictions (Table 3.6). Predictions based on screen level air temperature and relative humidity with a response time of 2 hours agreed closely with leaf bunch data over a range of moisture contents from 5 to 30 per cent, and were superior to predictions from either the CBEF or GFDM models.

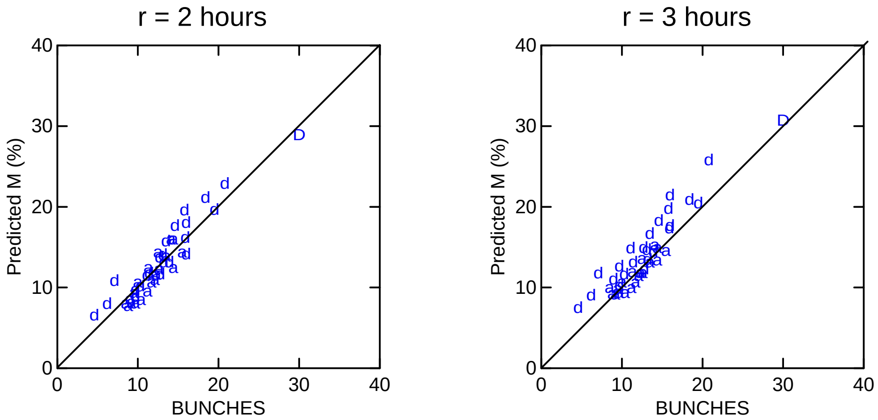


Figure 3.12 Moisture content of leaf bunches plotted against predictions from Nelson's model based on screen level temperature and relative humidity. Predictions are for response times of 2 and 3 hours. Symbols d and a indicate samples collected during desoprtion and adsorption conditions respectively, and D indicates a sample affected by dew.

TABLE 3.6

Error statistics for predictions of leaf bunch moisture content from the CBEF, GFDM and Nelson's model over five days of sampling at the Stirling Range (n = 43). Predictions from Nelson's diurnal EMC are for response times of 2 and 3 hours and relate to screen level temperature and relative humidity.

Model	MAE	RMSE	MB
Nelson EMC			
$r = 2$	1.27	1.58	-0.36
$r = 3$	1.66	2.17	-1.29
CBEF	2.14	3.44	1.37
GFDM	3.19	4.37	-0.92

3.2.5 Discussion

The moisture content of fine dead fuels in mallee-heath may vary substantially over the diurnal cycle in response to changing environmental conditions. This was clearly illustrated during the experimental run conducted at the Stirling Range on 25 February 1992 where the moisture content of litter baskets and leaf bunches reduced by more than 20 per cent in only six hours. Dead fuel moisture content also varied according to the type of fuel particle and the conditions of exposure. During daytime conditions, litter on the ground was consistently drier than elevated dead fuel suspended in shrubs or as leaf bunches. Mallee-heath has an open canopy which does not provide a high degree of shading for litter and elevated fuels, and solar radiation may therefore have a substantial affect on the surface temperature of fuel particles. Litter fuels exposed to full sunlight were found to have surface temperatures up to 30°C above the ambient air temperature, but tended to be somewhat cooler than ambient in the early morning and late evening when the intensity of solar radiation was low. Elevated dead fuels in mottled shade tended to be only slightly hotter (up to 5°C) than ambient, due to the combined effects of shading and elevation above the ground surface. Countryman (1977) drew attention to the importance of solar radiation effects on fuel moisture content and noted that in *Pinus ponderosa* stands the history of exposure of the litter bed to radiation could be more important in determining its moisture content at any given time than the environmental conditions at that time.

The CBEF and GFDM models consistently overpredicted the moisture content of shallow litter and litter baskets in mallee-heath, but showed better agreement with the measured moisture contents of deep litter under mallee clumps (M_{ld}) and elevated dead fuels (M_{de}) and leaf bunches. McArthur (1962) noted that the relationships on which the CBEF was based were typical of fuels receiving about 25 per cent of full sunlight, and so the overprediction for exposed litter fuels in mallee-heath is not unexpected. However, the tendency of the GFDM model to overpredict fuel moisture content is unlikely to be related to shading effects as the model was developed for open grasslands under clear sky conditions (McArthur 1966). Microclimate near the ground may have an important influence on the temperature and humidity conditions to which fuels are exposed (Arya 1988, Viney 1992). Exposure conditions for standing grass swards are more likely to approximate those for elevated dead fuel than those for shallow litter or litter baskets in mallee-heath, hence the better agreement between model predictions and elevated dead fuels than litter fuels. Results from the experiment conducted at Perup indicate that screen level conditions provide a better representation of the exposure condition of leaf bunches than do temperatures measured at 0.5 m above ground in mottled shade. Use of the latter parameterisation of Nelson's model resulted in substantial underprediction of fuel moisture content, particularly for moister fuels undergoing adsorption (at night). From a practical standpoint, screen level conditions are easier to measure or model than conditions elsewhere in the low shrub layer and would be favoured as a basis for fuel moisture content prediction, provided that the accuracy of resulting predictions is acceptable.

The SMC for jarrah forest consistently overpredicted the moisture content of both shallow and deep litter and does not appear suitable for monitoring the moisture content of litter fuels in mallee-heath. This model was developed for use in open forest 20-30 m in height with a 60 per cent canopy cover. Litter fuels in mallee-heath would tend to dry much faster than those in jarrah forest due to the greater exposure to solar radiation, as is the case with the CBEF model. The influence of wind on fuel drying would also tend to be greater in mallee-heath which is shorter and has a more open canopy than jarrah forest. Wind is most important in the estimation of fuel moisture content in the period immediately following rain when surface moisture may be present on leaves (Van Wagner 1979).

Nelson's diurnal EMC model gave predictions that were superior to any of the three empirical models tested. This model requires measured or estimated fuel level temperature and relative humidity as inputs to predict the EMC. Measurement of fuel level temperature and humidity is not generally practical in most field situations, but results from the evaluation conducted at the Stirling Range indicate that these can be estimated with reasonable precision from screen level weather observations using the relationships developed by Byram and Jemison (1943) and Nelson (1991). In situations where fuel level temperature must be estimated from screen level observations, further improvement in the accuracy of moisture content predictions from Nelson's EMC model may be possible through the use of a more sophisticated model than that of Byram and Jemison (1943). Viney (1992) demonstrated that a model based on the surface energy balance provided more accurate predictions of fuel level temperature and relative humidity than Byram and Jemison's equation or a similar empirical model developed by Van Wagner (1969). In Viney's study, these latter models tended to overpredict fuel temperature at night and gave better predictions over dry soils than over moist soils. The surface energy balance model is, however, considerably more complex and requires estimation of twelve separate parameters to predict surface temperature.

It is likely that the accuracy of predictions from Nelson's model would be improved by using values for constants *a* and *b* in equation 3.4 that are specific to mallee-heath fuels, and a more precise estimation of response time. Catchpole *et al*. (in press) used a spline interpolation technique to estimate the EMC as a function of fuel temperature and humidity from Nelson's (1984) semi-physical formulation. When fitted to the experimental data from Perup, the spline interpolation technique gave response times of 1.69 hours for litter samples, 2.05 hours for litter baskets and 3.98 hours for leaf bunches. These values are of the same magnitude, and in the same order as the estimates obtained in this study using a less sophisticated method (Tables 3.3 and 3.4). A further advantage of Catchpole *et al*.'s technique is that it provides fuel specific estimates of constants *a* and *b*, thereby obviating the need to use the equations of Anderson (1990b) which were developed for North American foliar types. Despite the use of first approximation values of *a*, *b* and *r* in this study, prediction errors were not that much larger than those obtained by Catchpole *et al*.. Comparative MAE values for Catchpole *et al*. and this study are as follows: 1.2 and 1.5 per cent for litter samples; 0.9 and 1.0 per cent for litter baskets; and 0.8 and 1.2 per cent for leaf bunches. The lower MAE values for litter baskets compared to litter samples found in both studies reflects the reduced sampling variability associated with the use of the repeated weighing technique. Litter samples provided a benchmark against which the basket moisture contents could be compared. Baskets provided an estimate of fuel moisture content that was within 2 per cent of the shallow litter under most conditions, except when there was substantial overnight condensation. This result confirms that the baskets were in fact representative of an intact litter bed. Similarly, leaf bunches provided a convenient and relatively accurate method for monitoring the moisture content of elevated dead fuel.

Leaf bunches used at the Stirling Range appeared to have a shorter response time than those used at Perup, even though the leaves used to prepare the bunches were collected from the same place and the bunches were prepared in the same manner. The reason for this difference is unclear, but it may relate to the degree of weathering experienced by the leaves used to prepare the different bunches. Fresh leaves of *D. drummondii* are fairly thick and waxy in appearance and it may be that the response time characteristics change as the waxy compounds are weathered following death of the leaf.

Fuel drying rates following rain were not specifically examined in this study. A considerable amount of additional data would be required to properly investigate the effects of rainfall intensity and duration on fuel drying trends in mallee-heath. Preliminary indications are that dead fine fuels in mallee-heath dry much more rapidly than predicted for litter fuels in open eucalypt forest by the SMC. The rapid drying of dew affected samples on 25 February 1992 is also consistent with this general observation. Based on current experience, it appears that prior rainfall is unlikely to influence the moisture content of shallow litter and elevated dead fuel after more than one dry day has elapsed. Deep litter may reflect rainfall effects for a longer period, perhaps up to five days. This is an important issue that merits investigation in any future studies of fuel moisture regimes in mallee-heath.

3.2.6 Conclusions

This study investigated the moisture content characteristics of three separate dead fuel components in mallee-heath, these being shallow litter beneath low shrubs, deep litter beneath mallee clumps, and elevated dead leaves from *D. drummondii* shrubs. These fuel components exhibit different diurnal patterns of moisture content which reflect the particular exposure conditions and inherent responsiveness of the fuel to environmental conditions. The diurnal EMC model proposed by Nelson (1991) was found to have considerable promise for predicting fuel moisture content in mallee-heath, and gave more accurate predictions than several commonly-used empirical models. An important advantage of this model is that it can predict the moisture content of different dead fuel components, provided that appropriate inputs for response time, and fuel level temperature and relative humidity are used. Experimental results demonstrated that moisture content predictions derived from screen level weather observations were only slightly less accurate than predictions derived from measured fuel temperatures. Preliminary observations suggest that dead fuels in mallee-heath dry much more rapidly after rain than is the case for litter fuels in open eucalypt forest.

3.3. Live fine fuels

3.3.1 Factors affecting the moisture content of live fine fuel

Tunstall (1991) reviewed the factors affecting moisture relations of higher plants, and discussed those most relevant to fire behaviour modelling in Australian vegetation types. The moisture content of living plants varies with plant organ, phenology, stage of development and environmental conditions. To a large degree the moisture content of particular plant tissues is species-linked but substantial variation may exist between individual plants from the same population due to factors such as aspect (Gary 1971) and degree of shading (Pook and Gill 1993), and between populations of a species at different locations (Philpot 1963, Loomis and Blank 1981).

Gravimetric moisture content, as a ratio of dry weight, tends to decrease with increasing tissue age due to the lignification and suberisation of cell walls (Tunstall 1991). Typically, young conifer foliage from the current seasons growth flush has a high moisture content (> 250 per cent) immediately following bud break but this declines progressively and approaches that of mature foliage (90-150 per cent) by the end of the first growing season (Van Wagner 1967b, Chrosciewicz 1986, Pook and Gill 1993). Conifer foliage older than one year undergoes a gradual but continuing decline in moisture content for up to four years (Gary 1971, Chrosciewicz 1986, Pook and Gill 1993). Blackmarr and Flanner (1968) reported a similar pattern for six species of shrub from North Carolina with young foliage having higher moisture contents than mature foliage originating from previous seasons growth. Tunstall (1991) noted that age-related effects on the moisture content of leaves from evergreen plants had been ignored in some studies because of the difficulty of stratifying foliage into age classes. Failure to account for such age-related effects could result in diurnal or seasonal patterns of variation in live tissue moisture content being obscured, particularly for plants which have a distinct flush of new growth at certain times of the year.

The relationship of live fuel moisture to environmental conditions may be of considerable importance where the climate is strongly seasonal and prone to extended periods without rain. This is the case in mediterranean climate regions including south-western Western Australia, where an excess of evapotranspiration over rainfall during the summer and autumn months gives rise to a substantial soil moisture deficit. The extent to which seasonal variation in soil dryness induces cyclic patterns in the flammability of live fuels will be influenced by the ability of the vegetation to exploit soil moisture and to control transpiration losses. Studies of the water relations of plants in south-west Australian forests and open woodlands have shown that both trees and understorey shrubs develop substantial water deficits during the summer drought (Crombie *et al.* 1988, Crombie 1992, Dodd and Bell 1993a, b). The rate of development, and severity of water deficits for trees and understorey shrubs in *E. marginata* forest on deep lateritic soils was negatively correlated to the rainfall at the site (Crombie 1992). Shallow-rooted plants developed lower water potentials and exhibited greater signs of water stress than medium to deep rooted species (Crombie *et al.* 1988, Dodd and Bell 1993a, b). However, these studies did not address the relationships between water stress and the moisture contents of foliage and fine twigs of living plants.

Distinct seasonal patterns in foliage moisture content have been observed for a range of trees and shrubs in North America (Dell and Philpot 1965, Jameson 1966, Van Wagner 1967b, Pirsko and Green 1967, Philpot and Mutch 1971, Green 1981, Chrosciewicz 1986, Weise *et al*. 1991) and southern Europe (Viegas *et al*. 1992, Valette *et al*. 1994).

At shorter time scales cyclic variation in environmental factors including air temperature, relative humidity and light intensity have the potential to affect plant water status and tissue moisture content (Leopold and Kriedemann 1975). Diurnal variation in foliar moisture content has been reported for a range of North American conifers (Philpot 1965, Jameson 1966) and understorey shrubs (Philpot 1965, Blackmarr and Flanner 1968). Tissue moisture contents were highest during the early morning and reached a minimum in the afternoon before commencing overnight recovery. This reflects a typical pattern of variation in plant water potential, and in general follows the inverse of transpiration and stomatal conductance. However, not all conifer species studied exhibited such a pattern, and results were not consistent between summer and winter (Jameson 1966, Gary 1971), clearly indicating that other factors may also have a significant effect on foliar moisture content. McCormick (1966) reported on a preliminary study of diurnal moisture content variation in *Acacia strigosa* Link., an understorey shrub in the Western Australian jarrah forest. The moisture content of foliage samples collected at two hourly intervals on three separate days showed a steady decline from above 160 per cent to below 130 per cent, although the extent of sample variation was not indicated.

The moisture content of fine live plant tissues may thus vary between species, and within a species may vary substantially according to the condition of individual plants. In studying the moisture content of live vegetation fuels the sampling technique employed can considerably affect the results obtained. To reduce overal sample variability, mature and juvenile foiage should be sampled separately and the time of day at which samples are collected should be standardised.

3.3.2 Experimental Methods

Live fuel moisture contents were studied for three species of shrub in mature mallee-heath at the experimental site described in Chapter 2. The shrub species studied were: *Dryandra drummondii* (Proteaceae), a short shrub comprised of loosely-packed live and dead leaves arising from a central rootstock; *Lambertia inermis* (Proteaceae), a single-stemmed shrub common in the intermediate stratum; and *Eucalyptus pachyloma* (Myrtaceae), a common mallee eucalypt at the site. These particular species were chosen to represent growth habits typical of shrubs in the different strata. All three species of shrub are evergreen and do not undergo any observable curing during the summer dry season.

Foliage characteristics were determined from samples of 30 live mature leaves of each species collected randomly from plants in the study area. To prevent desiccation, leaves were placed in plastic bags immediately after harvesting and returned to the laboratory, where they were processed the following day. The average thickness of each leaf blade was determined from three measurements made at random with a micrometer, and leaf blade surface area (one-sided) was measured using a suitably calibrated digitiser. Surface area (SA) to volume ratio was calculated for each leaf using the approximation of Brown (1970) that SA/volume ratio = 2/leaf thickness.

The moisture content of live foliage from each of the three shrub species was sampled at approximately monthly intervals between 23 October 1991 (Day 1) and 30 September 1992 (Day 346). Additional foliage moisture content data were available for *D. drummondii* from samples that had been collected in association with experimental fires conducted at the site during 1989 (October, November), 1990 (March, May, November) and 1991 (February, April). Where more than one set of samples were available for a particular month, the average value of these samples was used in analysis. In the case of *D. drummondii*, foliage was collected from five plants chosen at random from amongst a uniform population at the site. This technique was employed because individual plants did not have sufficient foliage to sustain repeated sampling. In the case of *L. inermis* and *E. pachyloma*, foliage was sampled repeatedly from the same five individuals of each species because removal of small quantities of foliage had only a negligible impact on the form and canopy density of these larger plants. On each sampling occasion 30-40 g (ODW) of leaves and petioles <2 mm in diameter were cut from the canopy of each plant, sealed in tins, and transported to the laboratory at Manjimup. Where new foliage growth could be clearly distinguished from mature foliage, material from both age classes was collected and processed separately using the same procedure. During the main study between October 1991 and September 1992, foliage samples were collected during the afternoon, generally between 1500 and 1700 hours. Foliage samples collected in association with experimental fires spanned the period from 1100 hours to 1600 hours. On all occasions foliage was free of surface moisture at the time of collection. In the laboratory, samples were weighed, oven dried for 18 hours at 105°C and re-weighed to determine moisture loss. Moisture content was expressed as a percentage of the oven dry weight of leaves in each sample.

Rainfall was recorded daily for the period of the study at Beulah Downs, 3 km south of the experimental site, and air temperature was recorded at the sampling site using a portable electronic weather station connected to a data logger. Daily values of the Soil Dryness Index (SDI) (Mount 1972) and the Keetch Byram Drought Index (KBDI) (Keetch and Byram 1968) were calculated using rainfall and air temperature. The SDI was calculated using a canopy interception function for open woodland and the appropriate evapotranspiration table from Burrows (1987). The KBDI was calculated using a computer program provided by Mr Kevin Tolhurst of the Victorian Department of Natural Resources and Environment, which utilises equations developed by Crane (1982). Both indices express the severity of drought in terms of mm of rainfall required to bring the soil back to field capacity. Indices were initialised at zero on 1 August 1991 following 150 mm of rainfall over the preceeding 30 day period.

Diurnal variation in live foliage moisture content was examined on 25 February 1992. Samples were collected on four occasions during the day (at 0800, 1200, 1500 and 1900 hours) from five plants of of each species. Foliage was collected and processed using the same procedure as for the monthly sampling. Air temperature, relative humidity and solar radiation were recorded throughout the day using a thermohygraph in a standard instrument shelter and an electronic weather station.

3.3.3 Results

Total rainfall at Buelah Downs between 1 October 1991 and 30 September 1992 was 507 mm, which is approximately 7 per cent above the annual average. Rainfall of 0.1 mm or greater was recorded on 124 days during this period. Monthly rainfall was highest in August 1992 (99.7 mm) and lowest in January 1992 (6.1 mm) (Figure 3.13).

Thunderstorms in late December resulted in monthly rainfall being almost three times greater than the average of 21 mm, but the total of 52 mm for the period January to March was slightly below the corresponding average of 63 mm. The longest period without rain was 35 days between November 20 and December 24; the longest rainless period preceeding monthly foliar sampling was only 15 days. On four occasions samples were collected on days following rainfall. Maximum air temperatures on days when foliage samples were collected ranged from 16°C to 31°C. Both the SDI and the KBDI rose steadily during spring and early summer 1991 to reach a peak in April before declining to a minimum in September 1992. The SDI indicated a higher and more sustained level of seasonal drought than did the KBDI. Values of the SDI and KBDI on days that *D. drummondii* was sampled in association with experimental fires ranged from 76 to 182 and from 14 to 121 respectively.

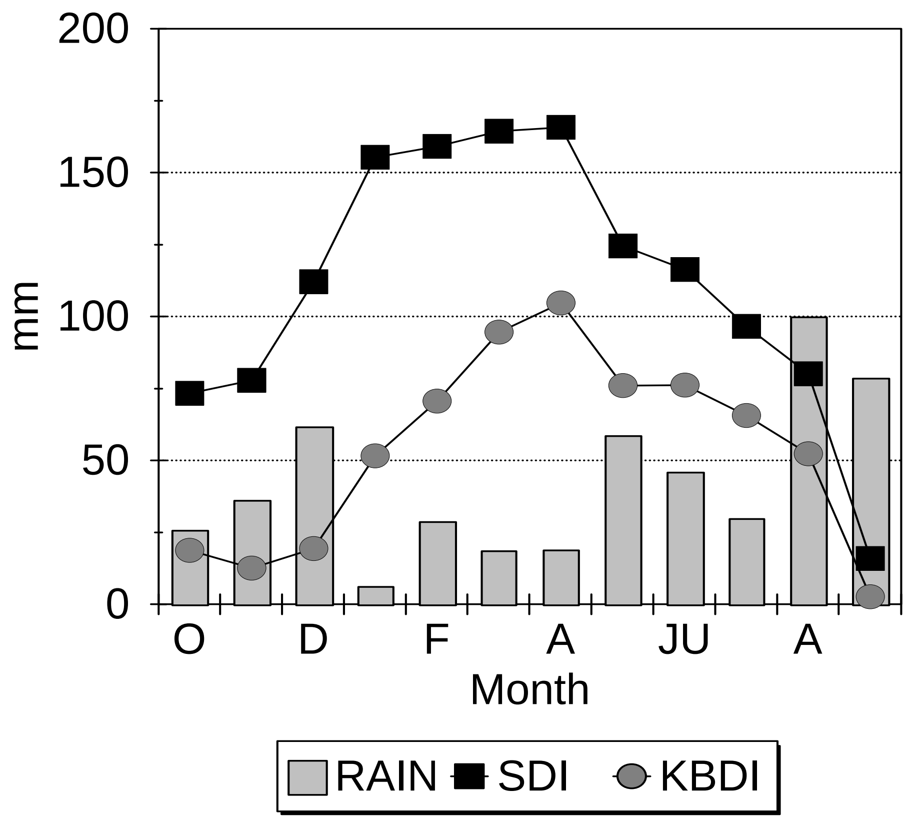


Figure 3.13 Monthly rainfall and values of the Soil Dryness Index (SDI) and Keetch Byram Drought Index (KBDI) for the period October 1991 and September 1992. Plotted values of the SDI and KBDI are for the days on which monthly foliage samples were collected for moisture content determination.

Leaf size and shape varied considerably between the three species (Table 3.7). The smallest leaves were those of *L. inermis* which were elliptical in shape and had a mean one-sided area of 89 mm^2, while the largest were those of *D. drummondii* which had a deeply lobed irregular margin and a mean one-sided area of 7611 mm^2. Leaves from *E. pachyloma* leaves were broadly lanceolate in shape and intermediate in size (967 mm^2). Leaf thickness ranged from 0.34-0.43 mm. Surface area/volume ratio was lowest for *D. drummondii* and highest for *E. pachyloma*.

TABLE 3.7

Mean one-sided leaf surface area and leaf thickness measured on samples of 30 leaves per species. Standard deviations are shown in brackets. Also shown is the average Surface Area to volume ratio for each leaf type, determined as 2/leaf thickness after Brown (1970).

Species	Leaf area (mm^2)	Leaf thickness (mm)	SA/Volume (m^{-1})
D. drummondii	7611 (2465)	0.43 (0.09)	4651
L. inermis	89 (25)	0.40 (0.01)	5000
E. pachyloma	967 (298)	0.34 (0.06)	5880

The mean moisture content of mature foliage samples collected between October 1991 and September 1992 was 97 per cent for *L. inermis*, 83 per cent for *D. drummondii* and 82 per cent for *E. pachyloma*. The overall mean for all samples of mature *D. drummondii* foliage collected between October 1989 and September 1992 was 82 per cent. Monthly means were plotted to investigate trends in mature foliage moisture content for each species (Figure 3.14). The honestly significant difference interval (HSD) (Andrews *et al*. 1980) calculated using the Tukey multiple comparison procedure is shown for each species. The moisture content of mature *L. inermis* foliage showed little variation from month to month (range 92-101 per cent) but there was greater variation in the moisture content of mature foliage from *D. drummondii* (range 78-93 per cent) and *E. pachyloma* (range 69-98 per cent). Sample variability was greatest in spring and early summer (October-January) for *L. inermis* and *E. pachyloma*, while *D. drummondii* samples tended to be more variable later in late summer and autumn (February-April). The mean square successive difference test (Zar 1984) was employed to test the null hypothesis that the month to month variation in moisture content followed a random pattern. This hypothesis was not rejected at the 5 per cent level for *D. drummondii* or *E. pachyloma* but was rejected for *L. inermis* which exhibited moisture contents above the annual average in the five months from November to March and below the annual average between April and August.

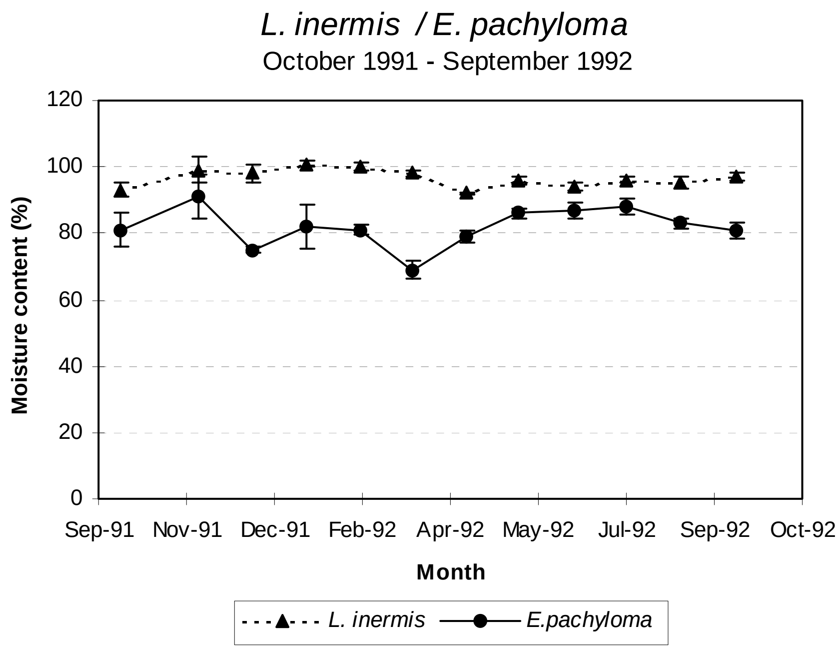
TABLE 3.8

Pearson correlation coefficients between weather variables, drought indices and mature foliage moisture content of three shrubs. Coefficients shown with an asterisk are significant at $P < 0.05$, and are based on 19 observations for *D. drummondii*, and 12 observations for *L. inermis* and *E. pachyloma*.

Variable	T	RAIN	SDI	KBDI	$M_{Dryandra}$	$M_{Lambertia}$	$M_{Eucalyptus}$
T	1.000						
LASTRAIN	0.411	1.000					
SDI	0.533	0.552	1.000				
KBDI	0.216	0.234	0.797*	1.000			
$M_{Dryandra}$	-0.391	0.256	-0.042	-0.117	1.000		
$M_{Lambertia}$	0.232	0.598*	0.147	-0.266	-0.164	1.000	
$M_{Eucalyptus}$	-0.564	-0.215	-0.487	-0.414	-0.014	-0.350	1.000

Explanation of variables:

- T = Maximum air temperature on the day of sampling (°C)
- RAIN = Number of days since last rain
- SDI = Soil Dryness Index on the day of sampling
- KBDI = Keetch Byram Drought Index on the day of sampling
- $M_{Dryandra}$ = Moisture content of mature *Dryandra drummondii* foliage
- $M_{Lambertia}$ = Moisture content of mature *Lambertia inermis* foliage
- $M_{Eucalyptus}$ = Moisture content of mature *Eucalyptus pachyloma* foliage



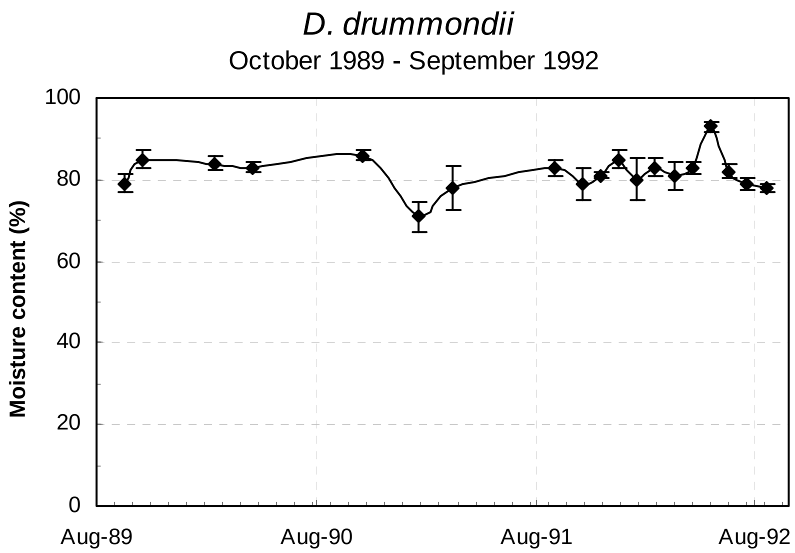


Figure 3.14 Monthly mean moisture contents of mature foliage collected from *L. inermis* and *E. pachyloma* between October 1991 and September 1992 and from *D. drummondii* between October 1989 and September 1992. Error bars indicate one standard error. Honestly Significant Difference intervals for each species calculated using the Tukey multiple comparison procedure are shown. Means separated by more than the HSD interval are significantly different at P = 0.05.

There was no significant correlation between the foliage moisture content of any of the three shrubs and either the SDI or the KBDI (Table 3.8). The moisture content of *L. inermis* foliage was positively correlated (P = 0.04) with the number of days since last rain, and there was a marginally significant negative correlation (P = 0.06) between the maximum air temperature on the day of sampling and the foliage moisture content of *E. pachyloma*. The SDI and KBDI were highly correlated, as would be expected given that both indices are calculated using air temperature and rainfall data.

Shoot growth takes place in late spring and early summer on all three species. New foliage growth was evident on *D. drummondii* in November, on all three shrubs in December, and on *L. inermis* in January. From February onwards new growth could not readily be distinguished from mature foliage that was one-year-old, or older. The moisture content of new shoots was substantially higher than that of mature foliage but reduced rapidly as the shoots developed. New shoots of *D. drummondii* had a moisture content of 196 per cent when sampled in November (Day 28) but this had declined to 137 per cent a month later (Day 69). New shoots of *L. inermis* exhibited a similar trend reducing from 122 per cent in December to 112 per cent in January (Day 93). New shoots of *E. pachyloma* had a moisture content on 125 per cent on the one occasion in December when they were sufficiently abundant to warrant sampling.

Mean foliage moisture contents recorded for each species on 25 February 1992 were close to those recorded for the full study period and exhibited a comparable level of variability (Table 3.9). There was little variation in the moisture content of *D. drummondii* or *L. inermis* throughout the day and an analysis of variance showed no significant difference between samples collected at different times of the day ($F = 0.925$, $p > 0.10$ and $F = 0.943$, $p > 0.10$ respectively). However, there was substantial variation in the moisture content of foliage from *E. pachyloma* and samples collected at 1500 hours were significantly drier than those collected during the morning. Differences between means were tested using the Tukey (1953) multiple comparison procedure. The moisture content of *E. pachyloma* foliage followed a similar trend to relative humidity and was the inverse of air temperature, but appeared to lag several hours behind the respective minima and maxima of these variables. Weather conditions on 25 February were typical for the time of year with a maximum air temperature of 26°C, minimum relative humidity of 31%, and south-easterly winds at 3-4 m s^{-1}. Peak solar radiation of 860 W m^{-2} occurred at 1300 hours.

TABLE 3.9

Air temperature (*T*), relative humidity (*RH*), solar radiation (*S*) and mean foliar moisture content for *E. pachyloma*, *L. inermis* and *D. drummondii* at four times on 25 February 1992. Figures in brackets are standard deviation of five replicates for each time of sampling. Means and standard errors of the mean for each species have been determined by pooling data (n = 20). In the case of *E. pachyloma* means shown with different letters were significantly different at p = 0.05.

Attribute	Time of sampling				Daily mean (SEM)
	0800	1200	1500	1900	
Weather					
T (°C)	21	26	24	18	n.a
RH (%)	50	31	41	76	n.a
S ($W\ m^{-2}$)	442	852	702	6	n.a
Moisture content					
D. drummondii	79.9 (3.7)	84.2 (8.9)	85.4 (5.0)	85.7 (6.1)	83.8 (6.2)
L. inermis	98.6 (4.1)	99.1 (2.8)	97.8 (3.1)	95.7 (3.6)	97.8 (3.4)
E. pachyloma	88.2^{a} (4.7)	84.6^{ac} (2.2)	71.7^{b} (5.3)	75.8^{bc} (2.8)	80.1 (9.0)

n.a = not applicable

3.3.4 Discussion

The three shrubs examined in this study maintained moisture contents of 70-100 per cent in mature live foliage throughout the year. There was no evidence of serial correlation in mature foliage moisture content for *D. drummondii* and *E. pachyloma.* Serial correlation was evident in the case of *L. inermis*, with a tendency for slightly higher moisture contents in summer and autumn. The overall extent of variation in foliage moisture content of *L. inermis* was, however, quite small. Although attempts were made to sample mature and young foliage separately, the relatively high variability of the *E. pachyloma* samples collected in October, November and January may have been due to the fact that some of the foliage which appeared to be mature was actually moist younger foliage from the 1991 spring growth flush. In this event, the apparent decline in average moisture content between October 1991 and April 1992 could be the result of leaf maturation rather than a response to plant water stress induced by summer drought. Tunstall (1991) commented that the difficulty in stratifying the age of foliage on Australian evergreen plants was responsible for much of the unaccounted-for variance in measurements of leaf water content.

The absence of a strong relationship between mature foliage moisture content and the soil moisture deficit over the summer months, as indicated by the SDI and the KBDI, is consistent with the drought tolerant nature of mallee-heath vegetation. Native plant communities in south-western Australia exhibit a range of adaptations to drought, including deep rooting and the ability to restrict transpiration (Crombie *et al.* 1988, Crombie 1992, Dodd and Bell 1993a, b). Unseasonal heavy rainfall in December 1991 is likely to have delayed the onset of the summer soil moisture deficit, and may have resulted in a lower level of plant water stress than could be experienced in a more protracted drought period. In the case of *D. drummondii*, for which foliage moisture content data were available over a three year period, the mean and range of the data collected between October 1991 and September 1992 were very similar to those for the entire period. The only obvious outlier was the low moisture content (71 per cent) recorded in February 1991. These samples were collected three weeks after a spell of several days of extreme temperatures and strong dry winds, during which record maximum temperatures were recorded at many places throughout south-western Australia (Anonymous 1991). Patches of heat damaged vegetation were evident throughout the Stirling Ranges after this event, and it is possible that the unusually low foliage moisture content recorded several weeks later was a result of the extreme drying conditions. However, under more normal circumstances the foliage moisture content of *D. drummondii* appears to be relatively unresponsive to changing seasonal conditions.

There is some evidence that *E. pachyloma* is more responsive to environmental conditions than the other two shrubs, as demonstrated by the variation in moisture content during the sequence of sampling on a typical summer day, and the marginally significant correlation with the maximum air temperature on the day of sampling. Further sampling over a wider range of environmental conditions is required to determine the possible consequences for fire behaviour of such variation. In particular, the response of live foliage to high temperatures, low relative humidities and strong winds typical of extreme fire weather conditions is worthy of investigation. These conditions are when crown fires are most likely to occur, and when the effects of reduced moisture content in the crowns of mallee eucalypts may be most critical (Van Wagner 1977).

Mallee-heath shrubs had somewhat lower foliar moisture contents than reported for six species of South African fynbos shrub over an annual cycle by Van Wilgen *et al*. (1990). Fynbos shrubs exhibited mean moisture contents of 100-125 per cent, except during the summer months of January, February and March when moisture contents declined to slightly less than 100 per cent. Viegas *et al*. (1992) examined the moisture contents of shrubs from central Portugal, reporting considerable variation in foliage moisture content between species, and from year to year amongst the same species. Foliar moisture contents for *Calluna vulgaris* and *Chamaespartium tridentatum* typically remained in the range 50-100 per cent, while foliage of *Arbutus unedo* and *Ulex europaeus* was generally between 100 and 150 per cent moisture content. All four species exhibited a tendency for foliar moisture content to be at a maximum in May and June and at a minimum between August and October, possibly reflecting the maturation of shoots following a spring growth flush. Viegas *et al*. (1992) attributed the large inter-annual variation in foliar moisture content to differences in the amount and distribution of rainfall during the first six months of the year.

Seasonal variation in the moisture content of live shrub fuels is considered to have an important influence on fire behaviour in chaparral shrublands in southern California (Green 1981). Philpot (1963) reported that foliage from Whiteleaf Manzanita (*Arctostaphylos viscida*) declined from a maximum moisture content in spring (May) to a minimum in winter (January). The moisture content of mature Chamise (*Adenostoma fasciculatum*) foliage declined from 108 per cent in May to 58 per cent in early September, but increased back to 90 per cent by early December following 50 mm of rainfall (Dell and Philpot 1965). However, twigs, branches and stems of Chamise showed little, if any, seasonal trend in moisture. Weise *et al*. (1991) also found that the moisture content of foliage from four common chaparral shrubs was highest in spring and declined over the summer and autumn months. The largest change was observed for *Ceanothus crassifolius* which declined from a maximum of 145 per cent in March to a minimum of 60 per cent in August. Manzanita exhibited the least change, ranging from 76 per cent in December to 92 per cent in March. Observations of very low live fuel moisture content following prolonged droughts and during extreme drying conditions induced by Santa Ana foehn winds (Pirsko and Green 1967) suggest that in chaparral shrublands, live fuel moisture content, and hence shrub flammability, may indeed be relatively responsive to environmental factors. Strong seasonal patterns in the moisture content of shrubs have also been reported from other areas in the western United States, and both Olson (1980) and Brown *et al*. (1989) established statistically significant relationships between shrub foliar moisture content and the KBDI.

The moisture content of young shoots from the current season's growth flush was initially much higher than that of mature foliage, but declined rapidly as the shoots matured. As young shoots did not at any stage comprise a substantial proportion of the canopy volume on any of the three shrub species studied, the overall effect of the young shoots on the average foliar moisture content of the plants is likely to have been negligible.

3.3.5 Conclusions regarding live fuel moisture content

The three species of shrub examined in this study maintained mature live foliage moisture contents of 70-100 per cent throughout the year. Shrubs in mallee-heath communities from the southern sandplain of Western Australia appear to have foliar moisture contents that are comparable to those of shrubs from mediterranean environments in the United States and southern Europe, but slightly lower than those of shrubs in South African fynbos. The results of this study suggest that the extent of variation in foliar moisture content of *D. drummondii* during the year is less than for shrubs from these other plant communities. Additional sampling over at least another annual cycle is needed before firm conclusions are drawn about the relationship between seasonal conditions and the moisture content of foliage from *L. inermis* and *E. pachyloma*.

CHAPTER 4

EXPERIMENTAL STUDIES OF FIRE BEHAVIOUR IN MALLEE-HEATH

4.1 Introduction

There has been little formal investigation of fire behaviour in Western Australian shrublands to date, despite their widespread occurrence and fire-prone nature. In recognition of the lack of reliable fire behaviour data for Western Australian shrublands, an experimental buring program was conducted in 20-year-old mallee-heath at the Stirling Range National Park. The aims of the experimental burning program were to investigate the factors critical to the initiation and sustained spread of fires, and to identify factors that affect the forward rate of spread of fires. Experimental fires also provided the opportunity to observe flame dimensions and spotting behaviour over a broad range of burning conditions. The existence of a database of well-documented fires is an essential prerequisite for the evaluation of existing fire behaviour models that may be applicable to shrubland fuel types, and for the development of a new model specific to mallee-heath.

4.2 Fire behaviour models for shrublands

Despite the widespread occurrence of shrub-dominated plant communities in fire-prone mediterranean environments, fire behaviour has not been investigated to the same degree in shrublands as has been the case for forests and grasslands. This review examines a number of fire behaviour models that have been developed for shrubland fuel types. All of these models predict rate of spread as a measure of fire behaviour, and some also predict flame dimensions. Flame dimensions, although difficult to quantify precisely, are an important descriptor of fire behaviour. Most people can readily visualise the severity of a fire from a description of its flame characteristics, whereas descriptions based on forward rate of spread, fuel consumption, Byram's (1959) frontal fire intensity or a numerical fire danger index may mean little to those who are not familiar with fire behaviour in the particular fuel type in question. Flame dimensions have a direct influence on the difficulty of suppression of surface and crown fires in most fuel types, and also determine the ecological effects of fire on the above-ground components of the vegetation resulting from thermal damage to living plant tissues (Burrows 1994). However, Cheney (1990) stressed that the relationship between flame characteristics and fireline intensity is specific to a given fuel type and may not apply to other structurally-different fuels. Currently, there is no published information on flame dimensions for Western Australian mallee-heath fires.

Scale is an important consideration in experimental fire behaviour studies. Small plots are convenient to establish and can generally be ignited and burnt with the minimal resources available to most field-based experimenters (Alexander and Quintilio 1990). Fire behaviour can often be visually monitored or measured within plots of less than 1 ha provided that the vegetation is not too tall or dense, and that visibility is not obscured by smoke (Gill and Knight 1991). Where space and etablishment costs are an important consideration, smaller plots may also be favoured because of the greater replication that can be achieved. For a combination of these reasons most field experimenters have elected to use plots of 1 ha or less, as revealed in the preceeding review. Indeed, the experimental fires lit by Lindenmuth and Davis (1973) were less than 0.1 ha in size and were conducted within single clumps of vegetation partially enclosed within metal shields. The method of ignition and length of line ignited have also varied considerably between studies, and are always specified. Small plots may suffer from the disadvantage that experimental fires may not achieve the maximum rate of spread that is achievable under the prevailing weather conditions. Cheney and Gould (1995) found that the rate of forward spread of grass fires in fuels of uniform moisture content was related to the width of the head fire measured normal to the direction of fire travel, as well as to the wind speed. The width of head fire required to achieve the potential quasi-steady rate of forward spread for the prevailing conditions increased with increasing wind speed. Fire behaviour models developed from small plots therefore need to be validated against larger scale test fires or well documented wildfires (Lindenmuth and Davis 1973, Marsden-Smedley and Catchpole 1995b) to confirm that the predictions can be confidently extrapolated beyond the range of the original experiments.

The United States National Fire Danger Rating System (Deeming *et al.* 1977) provides five fuel models for shrub vegetation types (Models B, D, F, O and Q) which can be used in conjunction with the Rothermel (1972) fire spread model to generate indices of seasonal fire danger. Site specific fire behaviour predictions can also be generated using the Rothermel model by means of the BEHAVE system (Andrews 1986) which is capable of accepting inputs in the form of standard fuel models (Anderson 1982) or customised fuel models (Burgan and Rothermel 1984). Four of the 13 standard fuel models for fire behaviour prediction are specific to chaparral and other shrub vegetation (Models 4, 5, 6 and 7; Anderson 1982). The BEHAVE system predicts flame length using the equation developed by Byram (1959) for pine litter with a component of grass.

Green (1981) has reviewed in detail the factors affecting fire behaviour in the chaparral shrublands of the south-western United States, noting the importance of fuel type and age, live and dead fuel moisture content, and topography. In one of the few field-based fire behaviour studies in chaparral, Lindenmuth and Davis (1973) conducted a series of 32 small (<0.1 ha) experimental fires in a stand of Arizona oak chaparral dominated by *Quercus turbinella.* They subsequently developed an empirical rate of spread model based on live foliar moisture content, air temperature, relative humidity, solar radiation and wind velocity. Despite the small size of the experimental fires, predictions from the model closely matched the behaviour of a high intensity wildfire and several larger-scale prescribed fires lit for model validation purposes (Lindenmuth and Davis 1973, J. Dieterich[1] pers. comm.).

Trabaud (1979) developed a fire spread model for an oak-dominated (*Quercus coccifera*) garrigue shrubland in southern France. One version of the model predicts forward rate of spread from wind speed and the height of the vegetation, while a second version takes into account fuel moisture content.

In South Africa, Van Wilgen *et al.* (1985) burnt fourteen small (0.25 ha) plots of fynbos shrubland over a wide range of weather conditions, with fire intensities reaching 21 000 kW m^{-1} in some plots. Observed rates of spread and flame lengths were significantly correlated (r^2 >0.7) with values generated using the Rothermel model and a fuel model developed specifically for fynbos shrubland (Van Wilgen 1984), provided that the estimate of fuel bed depth was adjusted from 1 to 1.4 m. This arbitrary adjustment had the effect of reducing the bulk density and packing ratio of the stylised fuel bed.

Aspects of the behaviour of fires in *Calluna* heathlands in Britain have been quantified by several authors including Kayll (1966), Thomas (1971) and Hobbs and Gimmingham (1984). Of these, only Thomas sought to establish a relationship between burning conditions and fire spread, concluding that headfire rate of spread in experimental gorse and heather fires was directly proportional to windspeed and inversely proportional to the bulk density of the undried fuel.

[1]. John H. Dieterich (retired), formerly Forester, United States Forest Service, Rocky Mountain Forest and Range Experiment Station.

Catchpole (1987a, b) examined the application of Thomas's gorse and heather model, and several configurations of the Rothermel model for predicting fire spread in uniform *Allocasuarina nana* heath and mixed-species coastal heath in southern New South Wales. Predictions from the various models were compared with the behaviour of experimental fires ignited along a 30 m line and allowed to burn with the wind for distances up to 100 m. The number of experimental fires in each fuel type was small (2 in *A. nana*; 3 in coastal heathland). Catchpole concluded that Thomas's gorse and heather model gave reasonable predictions in both fuel types, but that the multi-strata configuration of the Rothermel model advocated by Kessel *et al.* (1978) underpredicted spread rates in *A. nana* heathland. Flame length was well predicted by the equations of Byram (1959) and Thomas (1963), but flame residence time was underpredicted by the formula of Anderson (1969) which relates fuel particle flaming time to the surface area to volume ratio of the fuel.

Fire behaviour in buttongrass (*Gymnoschoenus sphaerocephalus*) moorland in Tasmania has been investigated by Marsden-Smedley and Catchpole (1995b), using experimental data from line ignition fires on 0.25 ha and 1 ha plots, together with observations from prescribed burns and high intensity wildfires. An empirical fire spread model developed using this data set included wind speed (at 1.7 m height above ground), dead fuel moisture content, and fuel age as significant variables. Flame height was found to be a function of dead fuel moisture content, fuel load and rate of spread. Spread rates predicted from the model compared well with data from a set of independent test fires ($r^2 = 0.85$) but flame height predictions were less satisfactory ($r^2 = 0.48$). The authors cautioned, however, that the fire behaviour predictions were themselves based on predicted values for dead fuel moisture content and should therefore be considered as a 'worst case' situation.

Until the commencement of the studies described in this thesis, the only significant experimental investigation of fire behaviour in a Western Australian shrubland had been undertaken by officers of the Western Australian Forest Department. Jones (1973, 1974) conducted a series of experimental fires in several different shrubland plant communities at the Stirling Range National Park with the intention of developing a guide for application of prescribed fire under mild spring and autumn conditions. Experimental fires were lit on 1 ha plots with point source ignitions or with short (10-20 m) lines of fire. Observed rates of spread were up to 0.07 ms^{-1}, but a number of the faster spreading fires did not attain a quasi-steady rate of spread before burning through the plot. Jones (1974) commented that the rate of spread of experimental fires was related directly to wind speed, and appeared to approximately double for each 5 per cent decrease in dead fuel moisture content. He also noted that fuels dried very rapidly, and could be ignited within one or two days of heavy rain. Unfortunately, this project was discontinued before the full program of experimental burning and associated fuel drying studies could be completed. While the 1973-74 study provided some useful observations about fire behaviour in shrublands, there was insufficient data with which to develop a fire spread model.

The shrublands discussed in this review may conveniently be categorised according to the nature of the substrates on which they occur. Buttongrass moorlands in Tasmania and *Calluna* heathlands in Britain typically occur on peaty soils which may remain waterlogged for much of the year, and are commonly termed wet heathlands (Specht 1981). In wet heathlands it is not uncommon for fires to spread within the shrub layer even though the soil is saturated. The other major group are the dry heathlands and shrublands which occur on mineral soils which are rarely, if ever, waterlogged. This group would include most chaparral communites, South African fynbos, *Allocasuarina nana* heathland and the mallee-heath shrubland which is the subject of this study.

Preliminary analysis of fire behaviour data from the studies reviewed above and from other unpublished sources indicates that it may be possible to define broad groupings of shrublands within which the relationships between wind speed and forward rate of spread, and between flame length and fire intensity are similar (Catchpole *et al*. 1998). Development of generic fire behaviour models for shrubland may therefore be possible. Such a model would need to take account of the effects of fuel characterisitics including depth, loading and particle size on fire behaviour. The effect of fuel moisture content on rate of spread would also need to be accounted for.

4.3 Experimental Methods

4.3.1 Experimental site

Experimental fires were conducted in mallee-heath at the Stirling Range National Park between October 1989 and May 1992. Site characteristics, vegetation structure, fuel characteristics and the layout of experimental plots have been described in Chapter 2.

4.3.2 Weather

Air temperature and relative humidity at 1.5 m above ground were recorded using a Lambrecht thermohygrograph in a standard instrument shelter (Stevenson screen) located about 0.5 km south of the experimental plots. The thermohygrograph remained at the site for the duration of the study and was periodically calibrated using an Assman aspirated psychrometer. For most of the period of the study, air temperature, solar radiation, wind speed and wind direction were also recorded using a UNIDATA weather sensor and anemometer located 2 m height above ground within a nearby stand of mallee-heath. This instrument was programmed to record mean values of each variable over intervals of 30 minutes. Data recorded with this instrument were subsequently used to develop an algorithm relating wind speed in standing mallee-heath vegetation to wind speed at 10 m height in the open. Rainfall was recorded at the site with a tipping-bucket raingauge.

During each experimental fire, except Plot R, wind speed and direction were measured at 2 m and 10 m height above ground (U_2 and U_{10} respectively) using UNIDATA combination anemometer/wind vane instruments connected to data loggers programmed to record the mean, minimum and maximum value every 30 seconds. Global solar radiation was recorded simultaneously. Instruments were located in the centre of a scrub-rolled buffer strip 50 m, or in some cases 250 m upwind of the plot to be burnt (Figure 4.1). Vegetation in these strips had been recently burnt and seldom exceeded 0.2 m in height. Data from these instruments located in open conditions were used in analysis of fire initiation and rate of spread.

Figure 4.1 Location of anemometers during experimental fires.

Due to equipment malfunction, wind data from 10 m height were not available for Plots E and N, and instead data from the 2 m anemometer were adjusted to 10 m height equivalent using equation C.3, details of which are provided in Appendix C.

In the case of Plot R, the wind speed at 10 m height in the open was determined using data recorded by the UNIDATA weather instrument sited at 2 m height above ground within the mallee-heath stand. This anemometer malfunctioned two hours prior to ignition of the plot, but observations made using the Beaufort scale suggest that the wind speed remained relatively constant from the time of malfunction until after completion of the experimental fire. The mean wind speed recorded during the 30 minutes prior to the anemometer malfunctioning was therefore taken to represent the wind speed at the time the plot was lit. Data from 2 m height were converted to 10 m height equivalent using equation C.5 (Appendix C).

4.3.3 Measurement of fuel moisture content

Five replicate samples (each 30-50 g ODW) of four fuel components were collected from nearby unburnt vegetation immediately following each fire, as follows:

- shallow litter (depth <10 mm) from the ground beneath the shrub layer (M_{ls});
- deep litter (depth 10-30 mm) from beneath clumps of mallee eucalpts, generally *E. pachyloma* (M_{ld});
- elevated dead foliage from *Dryandra drummondii* (M_{de}), a species of low shrub common throughout the study area which contributes substantially to the fuel load in the 0-0.4 m height stratum;
- elevated live foliage from *D. drummondii* (M_{fo}).

Most fires were of short duration and moisture samples were collected within 30 minutes of ignition which meant that the samples were representative of the conditions under which the fire burnt. Care was taken to collect moisture samples from areas of vegetation similar to that in the plot burnt by the experimental fire. Individual samples were sealed in air-tight tins and returned to the CALM laboratory at Manjimup where they were weighed and oven dried at 105°C for 18 hours and the re-weighed to determine moisture content. Moisture contents were expressed as a percentage of oven dry weight. The use of a single species as an index of live foliage moisture content avoided variability resulting from species-linked differences in moisture content (see Section 3.4).

There were several minor exceptions to the procedure described above. Firstly, only three replicate samples of each fuel component were collected for the fires conducted in spring 1989 (Plots I, J, K, and L), and deep litter beneath mallee was not sampled for the fire in Plot L. The number of replicates was subsequently increased to provide more precise estimates of moisture content, and to allow for the possibility of loss of samples during transit to the laboratory or processing as happened for some fuel components in Plots G, N, P, Q and R Secondly, in cases where two plots were burnt on the same day (Plots B and D; N and P) live foliage was only sampled following the first of the fires as it was assumed that the moisture content of this fraction would not vary significantly over the course of a few hours. Despite these variations in the sampling protocol, the moisture content of all four fuel fractions was estimated with acceptable precision, the proportion of plots in which the coefficient of variation was less than 0.2 being 100 per cent for M_{fo}, 83 per cent for M_{ls}, 77 per cent for M_{de}, and 71 per cent for M_{ld}.

4.3.4 Calculation of drought and fire danger indices

Drought conditions on the day of each experimental fire were described using the SDI and the KBDI. Rainfall data were available from the tipping bucket gauge at the site for all fires except those in Plots C and F; in the latter cases, rainfall data recorded at Buelah Downs, 3 km south of the experimental site were used instead. Air temperature data were available from the weather instruments at the study site for most of the study period. Gaps in the record of air temperatures were filled using data recorded at the CALM Ranger Stations at Moingup Springs and Bluff Knoll which are respectively 15 km north-west and 20 km north of the experimental site. The Bluff Knoll Ranger Station is on the opposite side of the main Stirling Range and summer maximum temperatures are typically 1-2°C higher and winter minimum temperatures 1-2°C lower than at the study site. The procedure used to initialise and calculate the two indices is detailed in Section 3.3.2.

4.3.5 Measurement of fire spread

Fire spread was measured using buried electronic timers equipped with a fusible link of resin-cored solder that melted on exposure to flames, thereby activating a digital clock (Plate 7). This technique for measuring fire spread was developed by Blank and Simard (1983). Timers buried on a standard 24 point grid within each plot prior to burning (Figure 4.2). At the completion of each fire timers were recovered and compared to a master clock that had been activated as ignition of the plot commenced.

The elapsed time between commencement of ignition and the arrival of fire at each grid point was then determined to the nearest second.

Grids were established prior to burning using a compass and a cotton hip-chain to measure distance, and were remeasured with a steel surveyors band following burning. Actual distances between grid points were generally within five per cent of those expected for a geometrically uniform grid, and standardised distances were therefore used for subsequent calculation of fire spread rate.

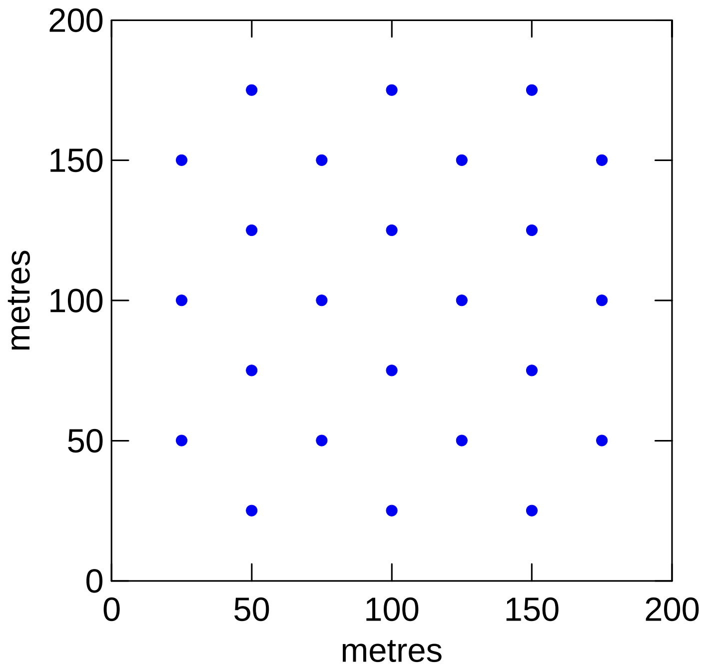


Figure 4.2 Location of electronic timers within each experimental fire, as shown by dots. An example of a right isosceles triangle defined by three adjacent timers is shown at the top left of the grid. At the top right of the grid is a cell comprised of four overlapping right isosceles triangles. Within the grid there are 13 such cells that do not overlap.

4.3.6 Conduct of experimental fires

The first of the experimental fires (Plot L) was lit with a line of fire extending half way along the north and western sides of the plot. This was done in an attempt to align the ignition line perpendicular to the prevailing north-westerly wind. After studying the development of this fire it was judged that a continuous line of fire lit along the side of the plot that was most perpendicular to the prevailing wind direction would have been equally satisfactory. All subsequent fires were initially ignited in this manner. A vehicle-mounted flamethrower fueled by kerosene was used to ignite the vegetation (Plate 8), except in the case of Plots F and R where hand-held drip torches were used. Ignition with the flamethrower took 1 to 2 minutes, and 2 to 3 minutes with drip torches. Wind direction changed substantially during the course of experimental fires in Plot B (from north to west) and Plot O (from east to north) and these plots were therefore re-ignited along the new upwind side. Substantial areas remained unburnt within some plots following the initial ignition, either because the prevailing wind direction during the fire had not been perpendicular to the ignition line, or because the flame front had not sustained. Any further lighting was delayed until the fire front from the initial ignition line had reached the other side of the plot or gone out.

4.3.7 Estimation of flame dimensions

The flame dimensions most commonly described in fire behaviour studies are flame length, flame height, flame angle, and flame depth (Alexander 1982). Flame length is defined as the distance from the tip of the flame front to the mid-point of the base of the active flaming zone. In this study the flaming zone was considered to extend to ground level, rather than to the top of the fuel bed. Flame angle defined as the angle between the flames and the unburned fuel bed ahead of the fire. Flame height represents the maximum vertical extension of the flame front. In defining flame length and height, occasional flaring above the general level of the flame front is normally ignored.

Flame dimensions were assessed visually from photographs of eight of the experimental fires for which good quality photographs and reliable estimates of forward spread were available. It was initially proposed that flame dimensions be measured photogrammetrically from stereo photo pairs, but this proved impractical due to problems caused by smoke obscuring the flames, and to the unpredictable spread direction of some of the experimental fires. Photographs taken using both colour and black and white infra-red film were used to estimate flame dimensions. A preliminary investigation indicated that the photographic images of flame fronts appeared similar regardless of which type of film was used and so estimates of flame dimensions made from either film type were regarded as being comparable. Flame length was the dimension of primary interest because of its relationship with fire intensity, and because it was readily estimated on most of the photographs available. Flame lengths were estimated to the nearest 0.5 m for flames up to 4 m long, and to the nearest 1 m for longer flames. Flame angles were also estimated from photographs, in classes of 15 degrees. Targets of known size were established in plots prior to each fire to improve the accuracy of visual assessments, and flames were also scaled against vegetation strata of known height. Examination of photographs revealed that the base of the flaming zone was mostly in the litter layer on the ground, and therefore flame lengths were taken from flame tip to the mid-point of the flaming zone at ground level, similar to the definition used by Andrews (1986). Forward rates of spread representative of the photographed section of the flame front were determined from the plotted fire spread isopleths, except in the case of Plots M and O flame where point observations of time and distance travelled by the fire were used to calculate the spread rate.

4.3.8 Estimation of fuel consumption

Fuel consumption was estimated visually at each of the 24 grid points following burning, including points burnt as a result of the initial and any subsequent lighting. Consumption of litter and live and dead shrub fuel components was assessed in four height classes (<0.4 m, 0.4-1 m, 1-2 m, >2 m) within 1 m radius of the point, as follows:

- percentage of litter consumed,
- percentage of dead shrub fuel consumed,
- mean diameter of live twigs consumed, in 1 mm classes. Visual estimates of stem diameter were initially calibrated against measurements made using steel calipers.

Plate 7 An electronic fire spread timer being collected at the completion of an experimental fire and compared with a master clock to determine the time at which the fire reached an established grid point.

Plate 8 Ignition of experimental fire in Plot E using a vehicle-mounted flamethrower.

4.4 Data analysis

4.4.1 Weather data

Most fires were completed within 15 minutes of ignition, and air temperature and relative humidity varied little within this period. Representative values for these variables were therefore taken directly from thermohygrograph charts. For wind speed, wind direction and solar radiation, 30 second mean values recorded by the data logger were averaged for the period used to define the forward spread rate of the fire front across the plot. A default period of 10 minutes was used in cases where fires failed to spread freely following ignition.

4.4.2 Analysis of fire spread using data from electronic timers

The forward rate of spread (*R*) of experimental fires was determined using data from the electronic timers. Due to equipment malfunction and the patchy nature of some fires timer data were not available for 24 points in every plot. Forward rate of spread was detemined using two methods; the first method involved fitting fire spread isopleths to the grid of timer data from which the spread of the headfire was then defined; the second method examined fire spread rate and direction across a series of triangles comprised of timers in the grid, following the procedure of Simard *et al.* (1984).

Isopleths representing the position of the fire front at successive time intervals were fitted to the grid of timer data for each plot using a contouring routine based on a distance-weighted least squares algorithm (McLain 1974) available in the SYSTAT for Windows statistical package (SYSTAT 1992). Isopleth maps were prepared at 1:1350 scale, except in the case of Plot E which was at 1:890 scale. The isopleth maps prepared for the experimental fire in Plot G is presented in Figure 4.3 as an example. The path of the headfire was identified from inspection of isopleth maps, and *R* then determined from the distance travelled by the fire front in a known time interval. These intervals varied from 200 seconds to 600 seconds duration depending on the rate of spread of the fire. The line over which fire spread was determined in each plot was selected so as to be approximately parallel (+/- 10 degrees) to the mean wind direction during the corresponding time period. Isopleth maps and the headfire paths defined from them were checked to ensure that they were consistent with visual observations of the fire spread, and with low oblique 35 mm still photographs and 8 mm movie film taken from an 8 m tall tower erected near each plot during the fire.

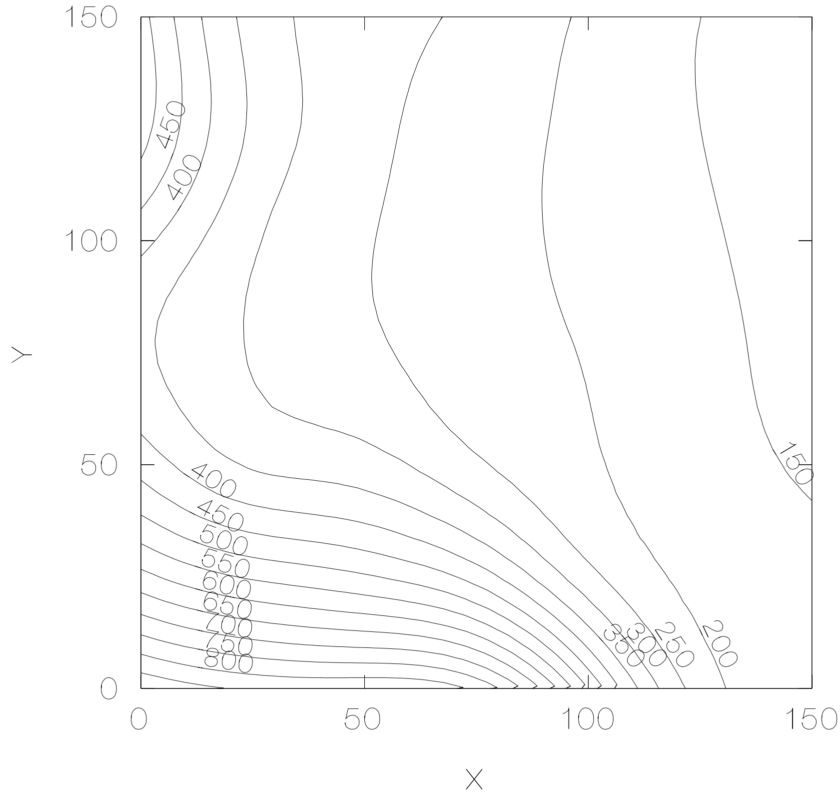


Figure 4.3 Fire spread isopleths fitted to timer data for Plot G. The time at which individual timers activated is shown. Times are in units of seconds, measured since the commencement of ignition. The interval over which the headfire rate of spread was determined is indicated by the arrow, and the average wind direction during the corresponding time period is shown on the compass in the top left hand corner.

The second method used to determine fire spread rate employed an algorithm developed by Simard *et al.* (1984) to calculate the direction and rate of spread across any triangle from three time measurements at the vertices of the triangle. Simard *et al.* (1984) also proposed a procedure for analysing the uniformity of fire spread given observations from four adjacent points. Where points can be established in advance of fire, as was the case with the experimental fires, calculation of fire spread is simplified considerably by using right isosceles triangles for which the direction of spread *Ø* is calculated as follows:

$$Ø = \tan^{-1} [\alpha(t_3 - t_1)/(t_2 - t_1) - ß] \qquad (4.1)$$

where

t_1, t_2, t_3 = times that a fire arrives at the first, second and third vertices of the triangle,

$Ø$ = the direction of spread across the triangle relative to a base line between t_1 and t_2

α, $ß$ = constants that assume values of 1 or 2, and 0 or 1 respectively according to the specific case being analysed (see Simard *et al.* (1984) for detailed explanation).

The rate of spread of the fire, R, across the triangle can then be determined from the relationship:

$$R = [\sqrt{\alpha}\, s \cos Ø]/[t_2 - t_1] \qquad (4.2)$$

where

s = length of the sides adjacent to the 90° angle in the triangle.

Where four time observations are available from adjacent points, the uniformity of spread rate and direction across each of the four included triangles can compared. Such comparisons can be used to assess the extent to which field data meet the underlying assumptions of the algorithm that fire spreads across the triangle as a straight line and at a constant direction and rate (Simard *et al.* 1984). Limits of acceptable variability for spread rate and direction based on four overlapping triangles in a square plot were proposed by Simard *et al.* (1984), as follows: the coefficient of variation of spread rate, C_R, should be less than 0.5 and preferably less than 0.2, and the standard deviation of the azimuth spread direction s_z should not exceed 21 degrees. Simard *et al.* (1984) did not discuss the reasoning behind these limits of acceptable variability, but they presumably reflect the collective experience of the authors in analysing fire spread.

Sixty equal-sized right isosceles triangles comprised of the immediately adjacent points in the 24 point grid were defined within each plot (Figure 4.2); for convenience these are referred to in subsequent sections as unit triangles. In practice, loss of data due to timer malfunction and to incomplete burn-out of plots frequently reduced the number of unit triangles for which fire spread could be calculated. The direction of spread, $Ø$, across each unit triangle was calculated on the basis of a standard side length, s, of 35.35 m, determined for a geometrically uniform grid. Because individual unit triangles were oriented in more than one quadrant it was necessary to convert calculated values of *Ø* to a standard azimuth direction, *z*, prior to comparison of spread direction. The rate of spread within each triangle was also calculated.

A series of thirteen square cells, each containing four timer points and four overlapping unit triangles was defined within each plot (Figure 4.2). Adjacent cells were non-overlapping, but included data from common timer points and were therefore not independent. Where data was available for all four unit triangles within a cell, the mean and standard deviation of *R*, and the azimuth spread direction, *z*, were determined and analysed for uniformity. Only those cells which had a coefficient of variation of 0.5 or less for rate of spread were used in determining *R* for the plot, following the recommendation of Simard *et al*. (1984). The cell, or cells, taken to represent the path of the headfire were selected so that the rate and direction of spread indicated by the triangulation method matched as closely as possible the path determined from the contouring method and from visual observations. Where more than one cell was included, the forward spread rate for the plot was determined as the arithmetic mean of the spread rate of the respective individual cells.

4.4.3. Statistical analysis

Data were analysed using the SYSTAT for Windows statistical software package (SYSTAT 1992). Scatterplots were generated to investigate relationships between pairs of variables. Relationships between weather, fuel moisture and fire spread were examined using a matrix of Pearson correlation coefficients generated for the data set, and subsequently by linear regression analysis of selected variables. Rate of spread data were log transformed prior to regression analysis to stabilise the variance, and to facilitate the fitting of non-linear functional relationships. Residuals (observed - expected) from regression equations were examined using scatterplots to determine the pattern of distribution and to identify trends in relation to environmental or fuel variables not already included in the regression model.

4.5 Results

4.5.1 Burning conditions for experimental fires

Eighteen experimental fires were ignited between October 1989 and May 1992, including all 16 of the 4 ha plots in the main grid and the two adjacent larger plots.

Burning conditions for each experimental fire are detailed in Table 4.1, and are summarised in Table 4.2.

Experimental fires were ignited over a wide range of burning conditions ranging from cool, moist weather in spring and late autumn to hot, dry weather in summer. At the outset of the program, mild burning conditions were selected in order to define the lower limits at which fires would spread, and to minimise the chance of fires escaping into adjacent unburnt plots. Fires were lit under more severe burning conditions as the project progressed, within the constraints imposed by the Western Australian Bush Fires Act which limits burning to days when the forecast Grassland Fire Danger Index (McArthur 1966) is 25 or less. However, one experimental fire was undertaken at a Grassland Fire Danger Index of 34 (Very High) due to actual weather conditions being more severe than anticipated by the fire weather forecast. The last two experimental fires to be conducted were lit during conditions specifically selected to fill gaps in the data set, these being respectively fires in dry fuels with light winds (Plot H), and fires in moist fuels with moderate to strong winds (Plot R).

Experimental fires were ignited between 1028 hours to 1550 hours (Western Standard Time) according to the prevailing weather conditions and the expected severity of fire behaviour. Wind speeds (U_{10}) during experimental fires ranged from 1.5 m s^{-1} to 6.9 m s^{-1} with a mean of 4.7 m s^{-1} (Table 4.2). Ten fires were lit under prevailing east to south-easterly winds, seven were lit under north to north-westerly winds associated with pre-frontal low pressure troughs, and one fire was lit with south-westerly winds. Cloud cover and solar radiation varied considerably during the course of some fires.

TABLE 4.1

Environmental conditions, fuel moisture content and drought indices for 18 experimental fires in mallee-heath. Data are means with standard deviations shown in brackets, where appropriate. n.a. = data not available

Date of burn (d/m/y)	Plot code	Time of Ignition (hrs)	Duration of observation (mins.)	Side of plot ignited	Weather						Fuel moisture content				Drought Indices	
					T (°C)	RH (%)	U_{10} (m s^{-1})	U_2 (m s^{-1})	Wind Direction (°mag.)	S (W m^{-2})	M_{ls} (%)	M_{ld} (%)	M_{de} (%)	M_{fo} (%)	SDI (mm)	KBDI (mm)
14/03/90	A	1350	7.0	S	20	48	4.5 (0.7)	2.8 (0.6)	159 (10)	448 (50)	6.7	8.8	12.0	88.0	160	97
20/02/91	B	1438	5.0	N	36	14	3.2 (0.4)	2.0 (0.4)	279 (13)	572 (118)	3.2	4.0	5.5	67.5	182	120
9/03/92	C	1528	10.0	E	31	40	4.8 (0.8)	2.9 (0.6)	116 (5)	481 (12)	7.0	8.0	8.6	80.9	168	91
20/02/91	D	1126	2.5	N	32	22	6.9 (1.0)	5.1 (0.5)	7 (7)	828 (6)	3.8	5.4	7.2	67.5	182	120
23/11/90	E	1115	5.0	E	20	55	4.9 (n.a.)	3.5 (0.8)	129 (6)	506 (97)	5.7	10.0	11.6	86.3	104	22
5/05/92	F	1415	10.0	W	22	52	5.6 (1.4)	3.5 (1.0)	318 (8)	250 (117)	14.3	31.8	15.8	80.4	165	107
19/02/91	G	1334	3.5	E	27	28	4.4 (0.9)	3.2 (0.6)	101 (9)	812 (3)	3.3	5.6	5.4	81.3	181	119
4/04/91	H	1402	10.0	N	31	16	1.5 (0.5)	1.2 (0.4)	243 (39)	603 (5)	6.7	7.2	10.0	77.8	164	121
6/11/89	I	1459	10.0	E	20	48	5.1 (1.2)	3.6	142 (9)	646 (7)	5.6	9.3	8.4	90.4	83	16
8/11/89	J	1044	3.5	E	21	55	6.7 (1.1)	4.8	84 (11)	909 (14)	5.4	10.0	8.9	85.6	85	18
7/11/89	K	1229	6.5	E	20	50	6.1 (1.1)	4.3	125 (23)	830 (16)	5.6	10.6	6.3	77.7	88	17
20/10/89	L	1352	10.0	N	22	38	4.2 (0.8)	2.9 (0.7)	303 (14)	459 (206)	8.7	n.a.	10.8	78.8	76	14
12/03/91	M	1550	10.0	E	22	63	3.6 (0.4)	1.9 (0.7)	74 (13)	278 (74)	9.4	11.5	12.2	86.5	159	96
24/11/90	N	1317	10.0	E	26	47	5.2 (n.a.)	3.7 (0.5)	28 (10)	840 (2)	4.8	8.3	8.5	87.2	107	23
15/03/90	O	1140	8.5	N	23	43	2.9 (1.3)	1.4 (1.1)	1 (21)	756 (27)	3.7	7.4	11.3	78.5	161	97
24/11/90	P	1028	6.0	E	23	55	3.4 (0.9)	2.6 (0.5)	105 (12)	898 (7)	5.0	8.3	10.0	87.2	107	23
21/11/90	Q	1346	10.0	S	23	63	4.6 (0.9)	3.3(0.7)	207 (10)	415 (129)	10.3	9.9	13.1	84.4	99	20
3/05/90	R	1400	n.a.	N	24	60	6.9 (n.a.)	4.9 (n.a.)	n.a.	271 (n.a.)	10.8	13.7	13.2	83.4	158	108

TABLE 4.2

Summary of environmental conditions and fuel moisture contents during 18 experimental fires in mallee-heath. Weather data are mean values for the period over which fire spread was determined, or for a default period of ten minutes for fires that did not sustain.

Variable	Symbol	Unit	Mean	Range
Air temperature	T	°C	25	20 - 36
Relative humidity	RH	per cent	44	14 - 63
Wind speed - 10 m open	U_{10}	m s^{-1}	4.7	1.5 - 6.9
- 2 m open	U_2		3.2	1.2 - 5.1
Solar radiation	S	W m^{-2}	606	271 - 912
Fuel moisture content		per cent		
- shallow litter	M_{ls}		6.6	3 - 14
- deep litter	M_{ld}		10.0	4 - 32
- elevated dead fuel	M_{de}		9.9	6 - 16
- live *Dryandra* foliage	M_{fo}		82	68 - 90

TABLE 4.3

Matrix of Pearson correlation coefficients between environmental and fuel moisture variables; n = 18 for all variables except M_{ld} where n = 17, and M_{fo} where n = 16.

	T	RH	U_{10}	U_2	S	M_{ls}	M_{ld}	M_{de}	M_{fo}
T	1.00								
RH	-0.80**	1.00							
U_{10}	-0.20	0.31	1.00						
U_2	-0.21	0.29	0.97	1.00					
S	0.11	-0.29	0.05	0.17	1.00				
M_{ls}	-0.34	0.52*	0.18	0.10	-0.81**	1.00			
M_{ld}	-0.41	0.44	0.30	0.19	-0.54*	0.84**	1.00		
M_{de}	-0.49*	0.61**	0.01	-0.09	-0.71**	0.83**	0.70**	1.00	
M_{fo}	-0.65**	0.67**	0.05	-0.16	-0.23	0.16	0.14	0.29	1.00

* Significant at 0.05

** Significant at 0.01

The shallow litter layer was consistently the driest of the dead fuel components and had a mean moisture content of 6.6 per cent (Table 4.2). The moisture content of deep litter was similar to that of elevated dead foliage but spanned a broader range. All of the dead fuel fractions were much drier than the live *D drummondii* foliage which had a mean moisture content of 82 per cent.

Relationships between weather and fuel variables were examined using Pearson correlation coefficients (Table 4.3). Coefficients were calculated over 18 plots, except for M_{ld} (n = 17) which was not sampled in Plot L, and M_{fo} (n = 16) which was not sampled in Plots B and N. The only significant correlation amongst the weather variables was between air temperature (*T*) and relative humidity (*RH*). The three dead fuel moisture content variables were significantly correlated with one another, and with solar radiation (*S*). In addition, M_{ls} was significantly correlated with *RH*, and both M_{de} and M_{fo} were significantly correlated with *RH* and *T*.

4.5.2 Development and spread of experimental fires

Twelve of the fires developed continuous flame fronts which persisted even in areas where fuels were light and variable. These fires spread freely following ignition, but the proportion of each plot that burnt as a result of the initial lighting depended on the direction of the wind in relation to the ignition line. Where the wind was approximately perpendicular to the upwind side of the plot, fires typically developed a broad arc shape with the headfire spreading through the centre of the plot and flank fires spreading out to either edge. This pattern of spread was exhibited by fires in Plots D, G, I, J, K, N, O and P where more than 75 per cent of each plot was burnt as a direct result of the initial ignition.

Substantial proportions of four plots that were burnt under fuel and weather conditions favourable for fire spread remained unburnt following the initial ignition. This pattern of fire spread was observed in Plots A, B, E and H and resulted from the wind being not perpendicular to the upwind side of the plot at the time of ignition, or from major shifts in wind direction (>90°) during the run of the fire. Areas that remained unburnt following the initial ignition burnt readily once they were re-lit with the prevailing wind direction, althought this was not done until the spread measurements on the main fire had been completed.

Five of the experimental fires failed to sustain and spread extensively beyond the initial ignition line. This group, which comprised Plots F, L, M, Q and R are subsequently referred to as non-sustaining fires. The characteristic feature of these fires was that the flame front failed to remain cohesive for more than a minute or two after ignition, so that the fire became fragmented. Flames only persisted in more favourable fuel situations such as continuous litter beneath clumps of mallee, and patches of low shrubs with a substantial component of elevated dead foliage. None of these fires spread to the downwind edge of the plot. Fire behaviour did not alter substantially following any subsequent lightings, but the proportion of the plot burnt out did increase because of the greater length of active front. Based on these observations burning conditions were judged to be marginal or unfavourable for fire spread. The behaviour of each of these fires is briefly described below:

> Plot F - half the length of the initial ignition line extinguished within 2 minutes of lighting, but flames persisted in mallee-clumps and dense patches of shrubs for up to 15 minutes. The maximum extent of fire spread was 25 m, generally much less. No further lighting was undertaken.
>
> Plot L - the flame front fragmented with separate fronts spread up to 50 m into the plot following the initial ignition, and following a second ignition 30 minutes later. Fire spread was largely confined to continuous litter beneath mallee clumps.
>
> Plot M - the initial ignition line fragmented into two fire fronts that spread up to 70 m into the plot, burning mostly in litter beneath mallee clumps. Flank fires from these fronts did not spread laterally more than about 10 m either side of the axis of fire spread. A second lighting undertaken 30 minutes later did not spread more than 50 m in from the edges of the plot.
>
> Plot Q - fuels ignited freely but the flame front became discontinuous within about 3 minutes of lighting, and did not spread more than 30 m into the plot. No further lighting was undertaken (Plate 9).
>
> Plot R - the ignition line fragmented within about 1 minute of lighting and flames only persisted in litter beneath clumps of mallee, spreading up to 30 m before extinguishing.

Plate 9 Fire behaviour at the southern end of Plot Q showing the development of the fire at 13:48, two minutes following ignition. Note the discontinuous flame front and the tendency of the fire to sustain only beneath mallee clumps where fuels were more continuous.

Plate 10 Fire behaviour on the eastern side of Plot C showing the extent of fire spread 8 minutes after the start of ignition. Note the burnt ground in the foreground, and the failure of the fire to extend into the sparse fuel type further into the plot. The marker post visible in the centre left of the photograph next to a mallee is 4 m tall.

The behaviour and spread of fire in Plot C was largely determined by the spatial distribution of fuel types within the plot. This plot contained two distinct fuel types; around the outer margins of the plot the fuel type was typical *E. tetragona* mallee-heath similar to that in the other plots, but in the centre of the plot the vegetation was much sparser and more discontinuous. A more thorough description of fuel loading, structure and species composition in this area is provided in Sections 2.5.1 and 2.5.2. A continuous flame front initially developed in the mallee-heath fuel type, but the fire abruptly ceased spreading once it encountered the sparser fuel type further into the plot (Plate 10). Further lighting 20 minutes later led to most of the mallee-heath fuel type within the plot being burnt out, but did not appreciably increase the extent of fire spread in the centre of the plot. Clearly, burning conditions at the time were favourable for fire spread in mallee-heath but not in the sparser fuel type.

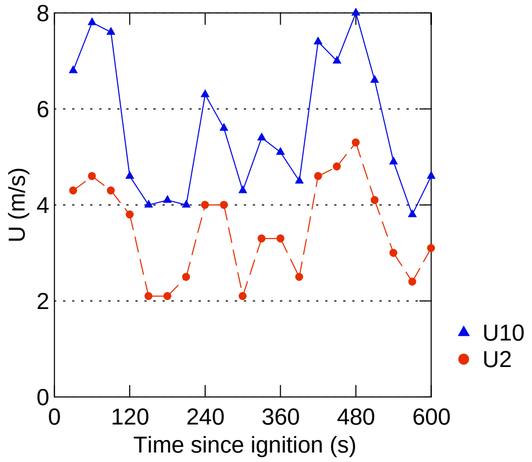
4.5.3 Factors critical to the initiation of fire spread

This phase of the analysis sought to discriminate burning conditions that were favourable for fire spread in mallee-heath from conditions that were not. Plot C was not considered in the analysis because the pattern of fire spread in was clearly affected by spatial variation in fuel characteristics. For the remaining 17 plots, environmental conditions appeared to be determine whether or not fires sustained and spread following ignition.

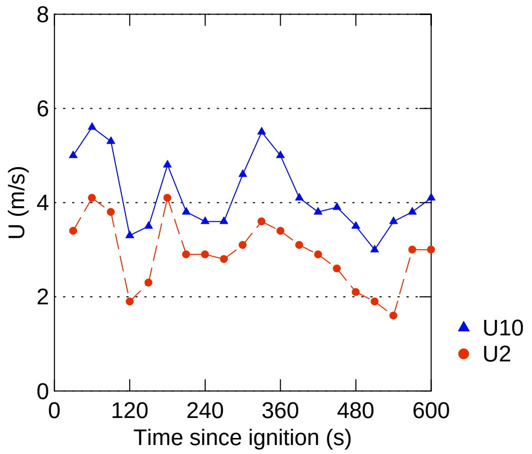
Variability of wind speed during the course of selected experimental fires was examined to investigate whether lulls in wind speed during the period immediately following ignition could account for the failure of some fires to spread. Trends in U_{10} and U_2 were examined during the ten minute period following igntion for three fires that failed to spread (Plots F, L, & R) and for three fires (Plots G, H & N) that did spread extensively (Figure 4. 4). The latter three plots were selected because they spanned a range of wind speeds, and because they were typical of the variability in wind speed encountered during experimental fires(coefficients of variation >20 per cent). U_2 followed a similar pattern to U_{10} during each of the fires. For the three fires which spread (Plots G, H and N), U_2 remained less than 3 m s^{-1} during the initial 1.5 minute period after ignition. In contrast, U_2 consistently exceeded 3.5 m s^{-1} during the first 1.5 minutes after ignition of Plots F and R; for Plot L, over the same period U_2 was between 3.5 and 3 m s^{-1}. On this evidence, the failure of fires to sustain and spread could not simply be attributed to lulls in wind speed in the first few minutes following ignition.

Figure 4.4 (below) Variation in U_2 and U_{10} during the ten minutes following ignition for three experimental fires that failed to spread (Plots F, L, and Q) and three fires that did spread (Plots G, H and P).

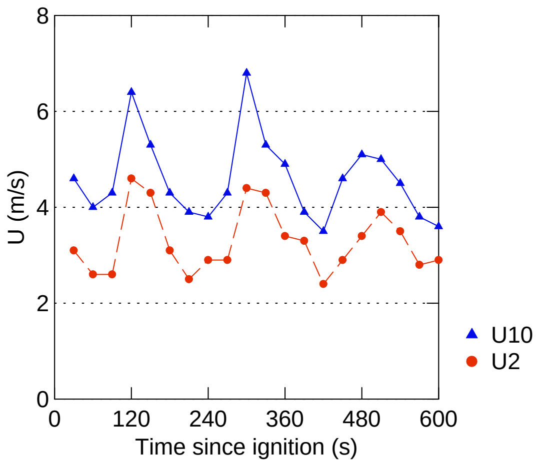
Plot F



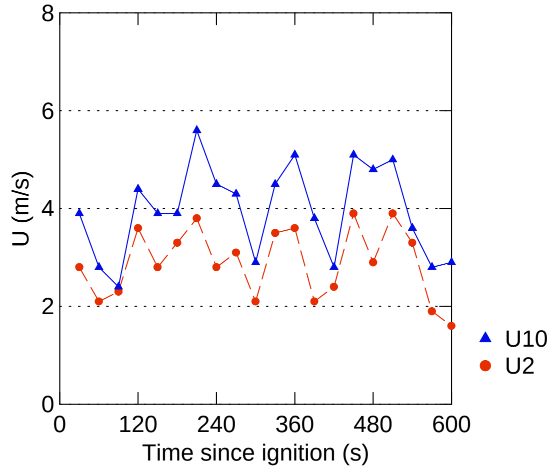
Plot L



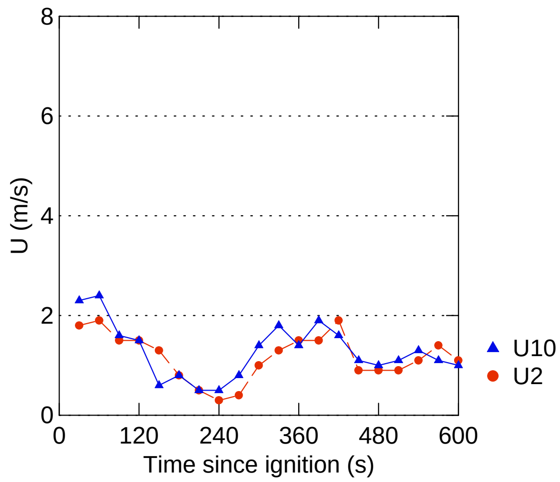
Plot Q



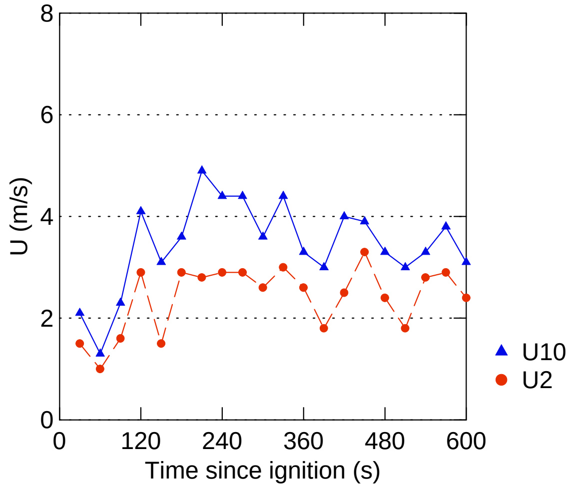
Plot G



Plot H



Plot P



Next, an exploratory analysis of the factors critical to sustained fire spread was undertaken using scatterplots (Figure 4. 5 a & b) with a range of environmental and fuel moisture variables plotted against wind speed (U_2). Mean values of T, RH, S and U_2 for the duration of the fire or for the 10 minute default observation period were used. Neither T or RH clearly discriminated between the fires that spread and those that did not. Fires that did not spread following ignition were consistently associated with higher moisture contents for each of the dead fuel components sampled (Figure 4.5 b). The variable which most clearly distinguished the fires that spread freely from those that did not was the moisture content of the shallow litter layer, M_{ls}. Fires spread freely in all plots where M_{ls} was below 8 per cent (Figure 4.5 b), regardless of wind speed. Fire spread was discontinous and patchy in plots where M_{ls} was between 9 and 11 per cent (Plots L, M, Q and R), and negligible in Plot F where M_{ls} was 14 per cent. Scatterplots incorporating M_{de} and M_{ld} exhibited a similar patern to that for M_{ls} but did not discriminate as clearly between the fires that spread and those that did not. There was no association between live foliage moisture content, M_{fo}, and whether or not fires sustained and spread.

There was also evidence that solar radiation affected the likelihood of a fire sustaining, and no fires sustained under heavy overcast conditions when S was less than 400 W m^{-1}.

4.5.4 Comparison of forward rate of spread (R) derived using contouring and triangulation methods

Fire spread isopleths were not defined for the five plots in which fire failed to spread extensively following the initial lighting (Plots F, L, M, Q, R) or in Plot C where the pattern of fire spread was strongly influenced by the spatial distribution of fuel types. The small number of timer points burnt in these plots also precluded calculation of fire spread rate using the triangulation method, except in Plot L where timer data were available from one cell of four adjacent points that did burn. However, the rate of spread estimate from this cell was not considered reliable because the coefficient of variation of R was 0.67, which exceeds the limit recommended by Simard *et al*. (1984).

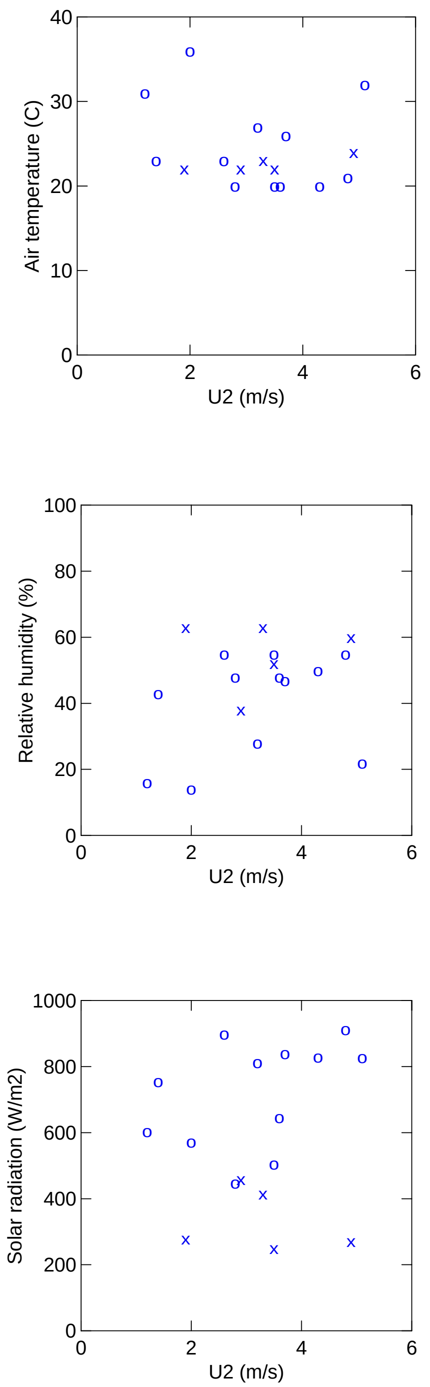


Figure 4. 5 a Scatterplots showing air temperature, relative humidity and solar radiation in relation to wind speed (U_2) for each of 17 experimental fires. Fires which spread following ignition are represented by circles (o) while fires which failed to spread are represented by crosses (x).

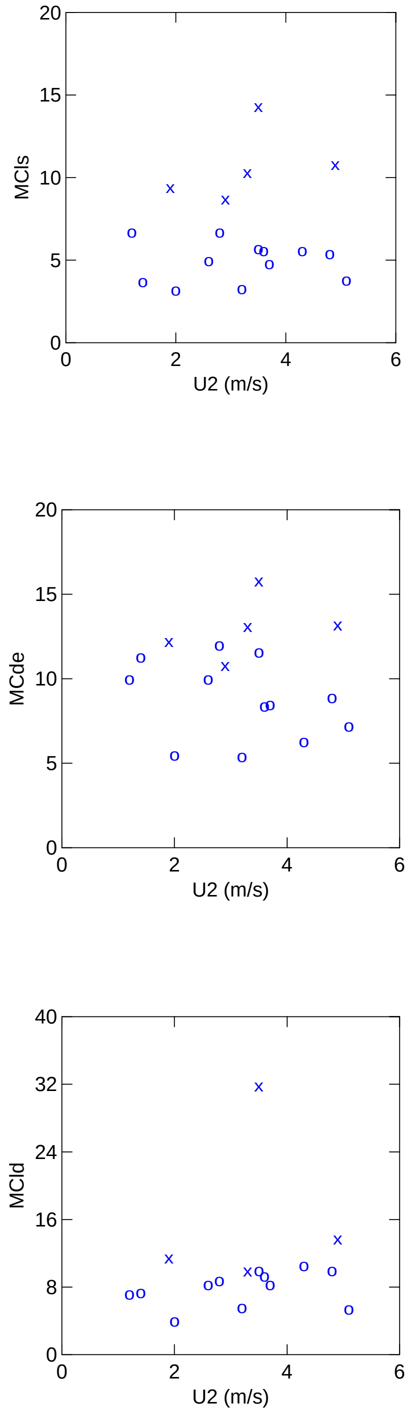


Figure 4. 5 b Scatterplots showing moisture content of shallow litter, elevated dead fuel and deep litter in relation to wind speed (U_2) for each of 17 experimental fires. Fires which spread following ignition are represented by circles (o) while fires which failed to spread are represented by crosses (x).

Isopleths fitted to the timer data for Plots B, I and N were considered unsuitable for defining rate of spread. Plot B was unsuitable because the fire front exhibited obvious deceleration after about 200 seconds from the time of ignition, and because the direction of fire spread apparent from both the isopleth and the triangulation methods was more than 20° different from the mean wind direction during the corresponding period. Plot I was also considered unsuitable because the apparent direction of fire spread was more than 20° different from the prevailing wind direction, with the result that most of the plot was burnt by a flanking fire. Isopleths for Plot N were unsuitable for determining rate of spread as they indicated continued acceleration of the headfire, and did not match the photographic records of the fire. The direction of spread in Plot N indicated by the triangulation method was also not consistent with the prevailing wind direction, probably because the fire front divided into two distinct heads.

Forward rates of spread were determined for nine experimental fires using the isopleth method. Plot H was included in this data set despite the fact that the direction of fire spread (175°) was not consistent with the measured wind direction during the period of the fire run (243°). Photographs showed a distinct headfire moving from north to south in the plot under the influence of a northerly wind (Plate 11). Wind strength and direction were very variable during this fire, with U_2 averaging 1.2 m s^{-1} and gusts from north-west to due south being recorded (Table 4.1).

Plate 11 Experimental fire in Plot H eleven minutes after the commencement of ignition. The target visible in the flaming zone is 4 m tall, and average flame length is The headfire is well developed despite light wind conditions (U_{10} = 1.5 m s^{-1}).

The number of cells available for determination of R using the triangulation method varied from only one in Plots A and J to nine in Plot G. The average spread rate for the plot was taken as the average of the spread rates from individual cells.

Forward rates of spread of the nine fires for which reliable estimates were available are presented in Table 4.4. Spread rates determined from isopleths (R_i) ranged from a minimum of 0.128 m s^{-1} in Plot H to a maximum of 0.675 m s^{-1} in Plot D, while spread rates determined by the triangulation method (R_t) ranged from 0.160 m s^{-1} in Plot H to 0.721 m s^{-1} in Plot G. Forward spread rates determined using the two methods were strongly correlated (r = 0.90, P <0.001) (Figure 4.6), but R_i tended to be about 15 per cent greater than R_t. Both methods ranked Plots D, G and J amongst the three fastest spreading fires and gave the same rankings to the three slowest spreading fires.

The strong correlation between R_i and R_t indicated that either variable was potentially suitable for use in subsequent analysis and model development. R_i was preferred to R_t because it made more complete use of the timer data available from each plot, and required no greater degree of subjectivity in defining the path taken by the headfire. R_i was also more consistent with techniques used to determine rate of spread in other field-based fire behaviour investigations of line ignition fires (Alexander and Quintilio 1990, Cheney *et al*. 1993, Burrows 1994, Marsden-Smedley and Catchpole 1995b). In subsequent analysis, R is equal to R_i.

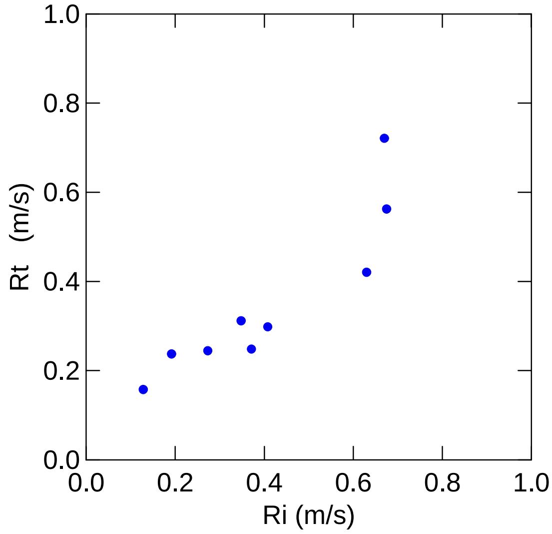


Figure 4.6 Comparison of forward rates of spread determined using fire spread isopleths (R_i) and the triangulation method (R_t) of Simard *et al*. (1984).

TABLE 4.4

Forward rates of spread determined for nine experimental fires using (a) fire spread isopleths (R_i) and (b) the triangulation method (R_t) of Simard *et al.* (1984).

Plot	Forward rate of spread (m s^{-1})					
	R_i	Rank	R_t	Rank	Difference (R_i - R_t)	Ratio R_i/R_t
A	0.408	4	0.298	5	0.110	1.37
D	0.675	1	0.562	2	0.113	1.20
E	0.273	7	0.244	7	0.029	1.12
G	0.670	2	0.721	1	-0.051	0.93
H	0.128	9	0.158	9	-0.030	0.81
J	0.630	3	0.420	3	0.210	1.50
K	0.348	6	0.311	4	0.037	1.12
O	0.192	8	0.237	8	-0.045	0.81
P	0.371	5	0.248	6	0.123	1.50

4.5.5 Variation in *R* with time since ignition

An important consideration in analysis and modelling of fire spread is whether or not the fire has attained a quasi-steady rate of spread which reflects the mean values of the environmental and fuel variables (Cheney and Gould 1995, 1997). Clearly, if the data used to develop a fire spread model have been collected from fires that are still growing and increasing in rate of spread, then the model will tend to underpredict the quasis-steady rate of spread typical of the later stages of fire development.

Variation in *R* with time since ignition was examined for eight experimental fires which had three or more consecutive periods over which spread was measured. The path taken by the headfire was determined from fire spread isopleths, and the corresponding distance travelled between successive isopleths calculated from scaled diagrams. Fire spread isopleths were at 50 second intervals on faster spreading fires or 100 second intervals on slow spreading fires. The number of periods for which *R* was determined varied from three to eight. Graphs were prepared showing *R* for successive time periods since ignition, with individual points representing the *R* over the preceeding period (Figure 4.7). Wind speed (U_2) over the corresponding period was

Figure 4.7

Figure 4.7

also graphed at 30 or 60 second intervals, with points representing the average speed over the preceeding interval.

An analysis of variance performed on the pooled data for all eight fires did not reveal a significant effect on *R* of time since ignition or wind speed ($P > 0.10$). Inspection of the data for individual plots revealed that only Plot O exhibited an obvious trend for *R* to increase with time since ignition. The increase in *R* was accompanied by a progressive increase in wind speed during the period of the fire. In Plot O, the highest value of *R* was recorded during the final observation period of the fire run ($0.30\ m\ s^{-1}$) and was about 30 per cent greater than the overall *R* of $0.19\ m\ s^{-1}$for the plot. For this plot, *R* was significantly related ($P = 0.01$) to time since ignition in a linear regression, while wind speed was only marginally significant ($P = 0.06$) when regressed against time since ignition.

This analysis suggests that most experimental fires had in fact attained a quasi-steady rate of spread, with the possible exception of Plot O. Values of *R* presented in Table 4.4 were therefore considered to reasonably represent quasi-steady rates of spread for the weather and fuel conditions prevailing at the time of each fire. Use of a non-quasi-steady rate of spread for Plot O was not considered likely to affect subsequent analyses to any large degree because the slow rate of spread of this fire meant that the actual change in rate of spread over the course of the fire was relatively small.

4.5.6 Relationships between weather variables, fuel moisture content and *R*

Scatterplots and correlation analysis were used to investigate the influence of environmental and fuel moisture variables on *R*, based on the subset of nine fires for which reliable estimates of spread were available. Wind speed was significantly correlated with *R*, with the correlation being slightly stronger for U_2 than U_{10} (Table 4.5). Figure 4.8 shows *R* plotted against U_2 and U_{10}. Correlations between *R* and other environmental and fuel moisture variables were relatively weak ($r < 0.5$), with the exception of M_{de} which was marginally correlated with *R* ($0.05 < P < 0.10$).

TABLE 4.5

Pearson correlation coefficients between forward rate of spread *R*, and environmental and measured moisture content variables for nine experimental fires. Correlations between *R* and predicted fine dead fuel moisture contents for eucalypt litter (CBEF and FFBT) and grassland are also shown; these variables are explained further in Section 4.5.8. Values of r significant at the 0.05 level are shown by an asterisk.

Variable	Correlation coefficient (r)
T	0.17
RH	-0.07
U_{10}	0.74*
U_2	0.76*
S	0.48
M_{ls}	-0.49
M_{ld}	-0.31
M_{de}	-0.62
M_{fo}	-0.19
FFBT	0.03
CBEF	-0.11
GFDM	-0.16

4.5.7 Effect of wind speed on *R*

The initial step in developing a model to predict *R* was to determine the most appropriate functional form to describe the relationship between wind speed and *R*. There was little difference in the strength of correlation between *R* and the two wind speed variables and so both U_2 and U_{10} were retained in this stage of the analysis. Equations of linear, power and exponential form were examined to determine which was the most appropriate to describe the relationship between wind speed and forwrd rate of spread. Each form of equation has previously been applied to wind speed functions in Australian fire spread models (Cheney 1981, Cheney *et al*. 1993). Power and exponential equations were fitted to the data using logarithmic transformations of *U* and *R* (Table 4.6).

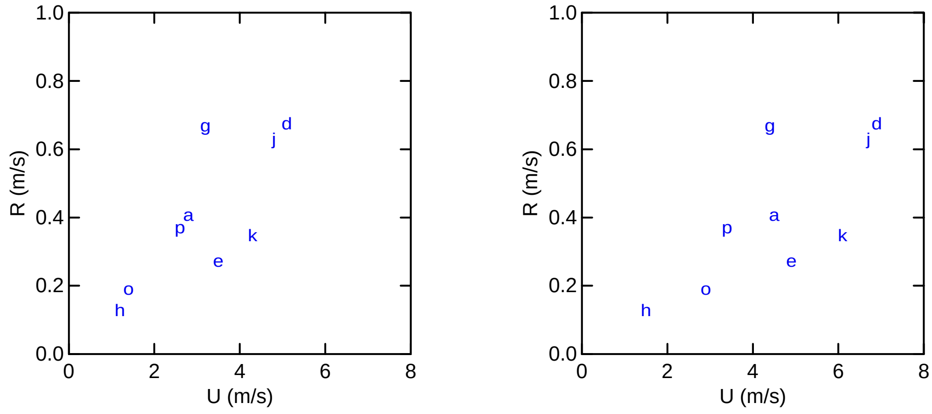


Figure 4.8 Relationship between *R* and U_2 (left) and U_{10} (right) for nine experimental fires. Individual fires are identified by letters. Lines show *R* fitted as a power function of *U* by the equations presented in Table 4.7.

TABLE 4.6

Equation forms evaluated for fitting a relationship between *R* and *U*. A, a, B and b are constants which assume different values in each equation.

Form	Untransformed	Transformed
Linear	$R = a + b\,U$	not applicable
Power	$R = A\,(U)^b$	$\ln(R) = a + b \ln(U)$
Exponential	$R = A \exp(bU)$	$\ln(R) = a + b(U)$

Power functions provided the best fit to the data and accounted for between 69 per cent and 72 per cent of the variation in *R* (Table 4.7). Exponential equations provided the next best fit, accounting for up to 64 per cent of variation in *R*, while linear equations accounted for up to 58 per cent of variation in *R*.

TABLE 4.7

Equations describing R as a function of U for nine experimental fires

Form	Equation	r^2	P
Linear	$R = 0.027 + 0.084(U_{10})$	0.54	<0.05
	$R = 0.047 + 0.113(U_2)$	0.58	<0.05
Power	$R = 0.088(U_{10})^{0.98}$	0.69	<0.01
	$R = 0.131(U_2)^{0.95}$	0.72	<0.01
Exponential	$R = 0.113\exp(0.25U_{10})$	0.63	<0.05
	$R = 0.123\exp(0.34U_2)$	0.64	<0.01

4.5.8 Effect of fuel moisture content on R

Dead fuel moisture content was considered the next most likely factor to affect R after the effect of wind speed had been accounted for. This assumption was based on the relative strength of the correlation between R and a range of experimental variables (Table 4.5), and the findings of a number of field and laboratory studies of fire behaviour (for example Anderson and Rothermel 1965, McArthur 1967, Peet 1971, Gill *et al*. 1978, Forestry Canada 1992, Cheney *et al*. 1993, Burrows 1994, Marsden-Smedley and Catchpole 1995). A series of candidate variables which described, or were related to, dead fuel moisture content were evaluated. These included the three direct measures of dead fuel moisture content sampled during each experimental fire (M_{ls}, M_{ld}, M_{de}) and two composite variables representing the average moisture content of the shallow litter and elevated dead fuel ($[M_{ls} + M_{de}]/2$) and the average moisture content of the deep and shallow litter layers ($[M_{ls} + M_{ld}]/2$). In addition, dead fuel moisture contents predicted by several widely used fire behaviour models were evaluated; these were the Control Burning in Eucalypt Forests guide (CBEF) and the Mark V Grassland Fire Danger Meter (GFDM) of McArthur (1962, 1977), and the Surface Moisture Content (SMC) from the Forest Fire Behaviour Tables of Sneeuwjagt and Peet (1985). Predicted fuel moisture contents have been found to be more strongly correlated with fire spread than measured values in some circumstances (Cheney *et al.* 1993). Air temperature, relative humidity and solar radiation can also directly influence dead fuel moisture content and so were evaluated for inclusion into the fire spread model. Candidate variables were added one at a time to the power function equations already fitted for wind speed (Table 4.8), and were evaluated on the basis of improvement in the goodness of fit (r^2) of the model and their respective P-values for inclusion.

TABLE 4.8

Statistics for candidate environmental and dead fuel moisture content variables added to a fire spread model based on a power function of wind speed (U_2 and U_{10}).

Variable	U_2		U_{10}	
	r^2	P value	r^2	P value
U only	0.72	0.004	0.69	0.006
U plus:				
M_{ls}	0.80	0.157	0.74	0.334
M_{ld}	0.84	0.069	0.82	0.073
M_{de}	0.74	0.459	0.75	0.263
$M_{(ls+ld)/2}$	0.85	0.065	0.80	0.118
$M_{(ls+de)/2}$	0.78	0.255	0.76	0.209
CBEF	0.76	0.312	0.79	0.132
GFDM	0.76	0.369	0.77	0.200
SMC	0.72	0.790	0.70	0.586
T	0.74	0.479	0.76	0.231
RH	0.74	0.519	0.74	0.341
S	0.75	0.419	0.73	0.371

The greatest improvement in r^2 was achieved by the addition of M_{ld} or the composite variables based on the mean of M_{ld} and M_{ls} (Table 4.8). Both variables approached the 5 per cent level of significance when added to the model based on U_2, but only M_{ld} approached significance when added to the model based on U_{10}. Residuals from equations fitted to U_2 and U_{10} were predominantly positive when M_{ld} was below 10 per cent and negative when M_{ld} was 10 per cent or greater, confirming the trend for fires to spread faster when the deep litter layer was dry (Figure 4.9). This finding supported the inclusion of litter moisture content as a variable in the final fire spread model.

Other fuel moisture variables (M_{de} and the composite variable $M_{(ls+de)/2}$) resulted in smaller improvement in r^2 values above those for the wind only model. Addition of direct environmental variables and dead fuel moisture content predicted by the CBEF and GFDM models provided slight improvement in the goodness of fit but none of these variables approached the 5 per cent level of significance for inclusion into the final spread model. Inclusion of SMC did not improve the goodness of fit of either model.

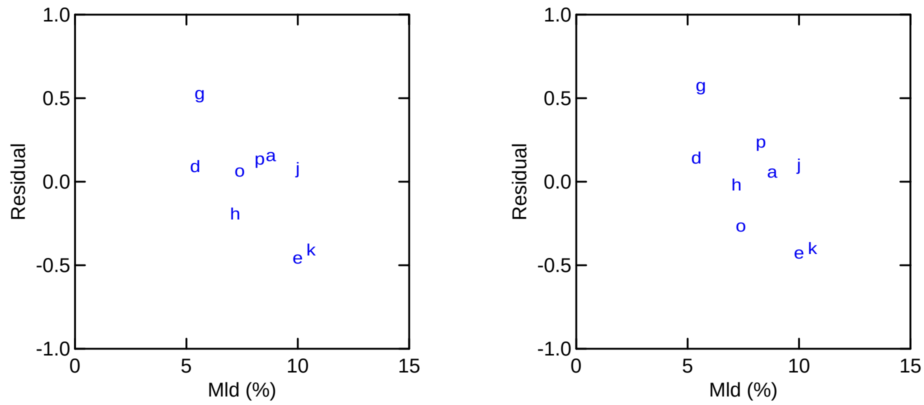


Figure 4.9 Residuals from equations describing R as a power function of U_2 (left) and U_{10} (right) plotted in relation to deep litter moisture content (M_{ld}) for nine experimental fires. Individual experimental fires are identified by letters.

The model chosen to describe the effect of wind speed and dead fuel moisture content on R was of the form:

$$R = aU_2^b \exp(cM_{ld}) \qquad (4.3)$$

where the constants a, b and c have values of 0.292, 1.05, and -0.11 respectively. This model explained 84 per cent of the variation in R (Table 4.8). Although the composite moisture variable $M_{(ls+ld)/2}$ resulted in a slightly higher r^2 value than did M_{ld}, the latter variable was preferred for inclusion in the model because of simplicity. The effect of wind speed on R was modelled as a function of U_2 rather than U_{10} because it consistently explained more of the variation in R, either alone or in combination with most of the dead fuel mositure variables. It should be emphasised that the U_2 term in Equation 4.3 represents the wind measured in open conditions where the ground cover is sparse and less than 0.2 m in height. For field application of the spread model, wind speed is more conveniently measured at 2 m height above ground than at 10 m height. Suitable areas for measurement of open wind at 2 m height include open pasture and stubble at the boundary of bushland reserves, recently burnt mallee-heath, scrub-rolled buffer strips and natural clearings such as salt lakes. In the event that forecast or observed wind speeds from 10 m height are used as the basis for a rate of spread prediction, U_{10} can readily be converted to an equivalent U_2 using Equation C.1 or C.2.

Forward rates of spread predicted by Equation 4.3 for M_{ld} values of 5 and 10 per cent are shown in Figure 4.10, together with the 90 per cent prediction bounds. Prediction bounds for rate of spread, R_p, were calculated as follows:

$$R_p = R \pm t_{0.95,\,\mathrm{edf}} \sqrt{\sigma} + \mathrm{var}(R) \qquad (4.4)$$

where edf is the error degrees of freedom from the regression model (n = 6), σ is the estimate of σ from model MSE, and:

$$\mathrm{var}(R) = \mathrm{var}(a) + U_2^2\mathrm{var}(b) + M_{ld}^2\mathrm{var}(c) + 2U_2\mathrm{cov}(a,b) + 2M_{ld}2\mathrm{cov}(a,c) + U_2\, M_{ld}\mathrm{cov}(b,c) \qquad (4.5)$$

where a, b and c are the constants for Equation 4.3. Covariances for the model were obtained using the REG procedure available in the SAS statistics package (SAS Institute 1985). Also shown in Figure 4.10 are the predicted rates of spread for each of the nine experimental fires used to develop the spread model, standardised at M_{ld} of 5 and 10 per cent respectively.

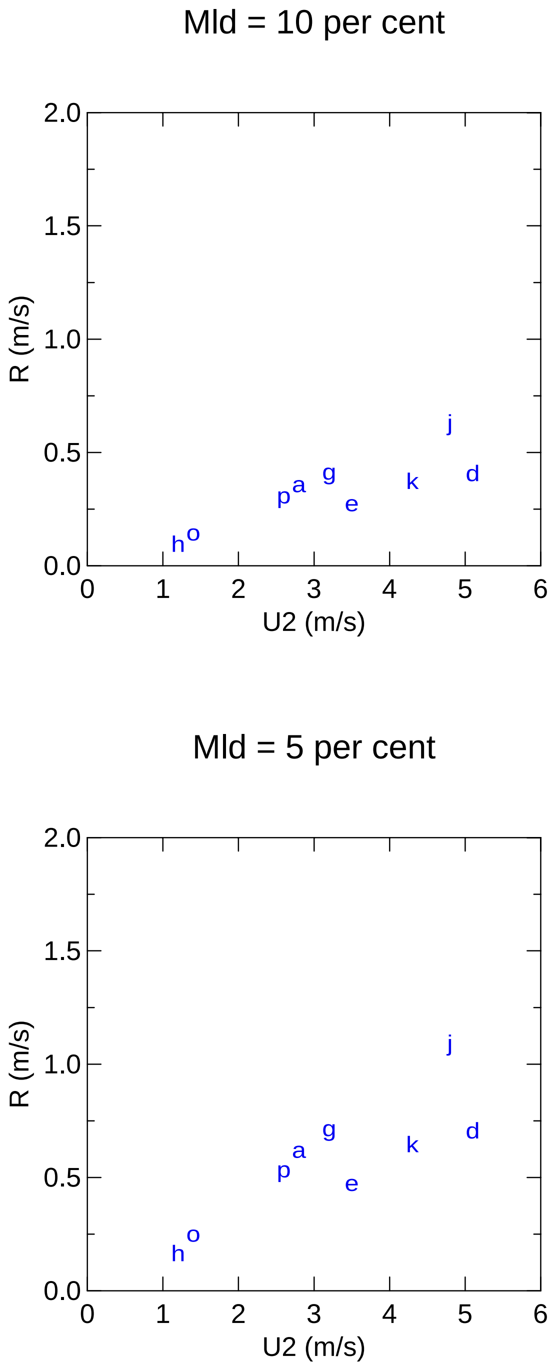


Figure 4.10 Forward rates of spread predicted by Equation 4.3 for M_{ld} values of 5 and 10 per cent. Individual experimental fires are identified by letters. The solid line shows the predicted value of *R* and the dotted lines represent the 90 per cent prediction intervals.

4.5.9 Effect of other environmental and fuel variables on *R*

The effect on *R* of variables other than wind speed and dead fuel moisture content was investigated by plotting the residuals from equation 4.3 in relation to values of the respective variables for each experimental fire (Figure 4.11). Variables examined in this manner were: the SDI and KBDI which reflect seasonal drought; live shrub moisture content (M_{lf}); and the percentage cover of mallee within each plot. The distribution of residuals did not show any pattern in relation to the SDI or KBDI. Residuals were also uniformly distributed with respect to M_{fo}, with the exception of Plot D where M_{fo} was substantially lower than in the remaining plots. There was some tendency for plots with a mallee cover below 50 per cent to have positive residuals (observed *R* > predicted *R*) and for plots with mallee cover above 50 per cent to have negative residuals (observed *R* < predicted *R*). However, the addition of mallee cover as a third variable to the fire spread model was not considered to be warranted, in view of the high proportion of variation in *R* already explained by U_2 and M_{ld} and the practical difficulties associated with estimating mallee cover in the field situation.

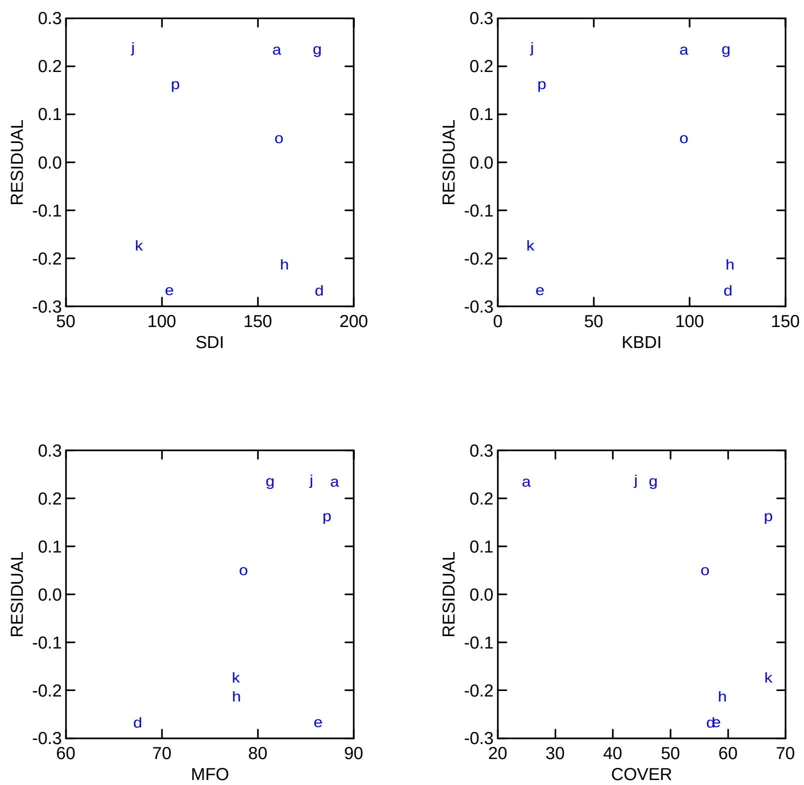


Figure 4.11 Residuals from Equation 4.3 plotted in relation to SDI, KBDI, M_{fo} and the percentage cover of mallee for nine experimental fires. Individual experimental fires are identified by letters.

4.5.10 Flame dimensions

Nine independent observations of flame length and flame angle were made from photographs, two of these being from Plot A. Flame observations were available from fires spanning a broad range of burning conditions, with average flame lengths ranging from 1 m to 11 m. Under light winds (U_{10} < 2 m s^{-1}), flame angles tended to be near vertical (75-90°) (Plate 12). Flame angles of 60-75° were typical of fires with forward spread rates of 0.1 to 0.4 m s^{-1} (Plate 11), while the two fastest spreading fires were characterised by flame angles of 45-60° (Plates 2, 13 & 14).

The relationship between *R* and flame length, F_L was linear over the range of experimental data (Figure 4.12), as described by the following equation:

$$F_L = 0.53 + 13.06\,R \qquad r^2 = 0.91,\ P<0.001 \qquad (4.6)$$

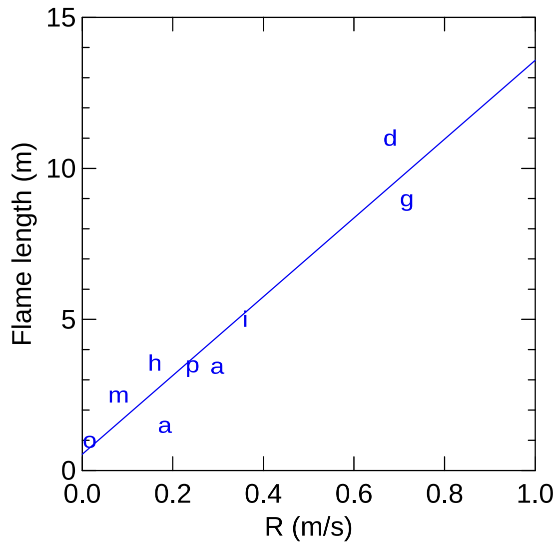


Figure 4.12 Relationship between *R* and flame length, F_L. Letters indicate the experimental fire to which the observation corresponds. The solid line fitted to the data is equation (4.6).

The largest flames observed during an experimental fire were in Plot D. Flame dimensions typical of this fire are illustrated in Plates 13 and 14 by means of a black and white infrared photograph taken from an 8 m tall tower, and a colour negative photgraphs taken from ground level at the same location. Both photographs were taken in the period between 4 and 5 minutes after the start of ignition, during which time the forward rate of spread of the fire averaged 0.68 m s^{-1} and the corresponding fire intensity was about 14 300 kW m^{-1}. A 4 m tall reference post fitted with a square target 0.6 m x 0.6 m is visible in the lower left hand corner of Plate 14 and gives an indication of scale. Scale can also be gauged from the vegetation, with the tallest shrubs and mallee eucalypts being between 3m and 4 m in height. Flames are consistently at least twice the height of the canopy (i.e. 8 m) with corresponding flame lengths of 10-12 m. Considerable flaring is also evident above, and in advance of the main wall of flames. The strong tilting effect of the wind on the flame front is apparent.

4.5.11 Spotting and fire spread across areas devoid of fuel

Observations made during experimental fires indicates that short distance spotting is not an important mechanism for fire spread in *E. tetragona* mallee-heath. Even the most intense fires did not ignite spot fires in unburnt fuel on the downwind side of the 100 m wide buffer strips, despite initial concerns to the contrary. This conclusion is based on observations from Plots D and G which had intense, fast-moving fire fronts driven onto the buffer strips by moderately strong winds (U_{10} of 6.9 and 4.4 m s^{-1} respectively). Dry conditions at the time of these fires (RH < 30 per cent, M_{ls} < 4 per cent and M_{ld} < 6 per cent) would have been conducive to ignition of spot fires, had there been any substantial spotting activity. The wind direction was perpendicular to the buffer strip during both fires, thereby minimising the distance that burning firebrands and embers had to travel before encountering unburnt fuel. In neither case were spot fires found to have ignited in the downwind plot.

The lack of spotting activity is most likely due to the scarcity of plant species with loose, fibrous bark which can be readily ignited and drawn aloft in the convection above the fire. Of the mallee eucalpts, only *E. marginata* has fibrous bark; the remainder have smooth gum type bark that does not accumulate as streamers on the stem. Spotting potential may be greater in other mallee-heath communities which include a greater density of trees and shrubs with fibrous bark.

Direct flame contact is the primary means by which fires in mallee-heath spread across sparse fuels or areas devoid of fuel. This was clearly observed in Plot D where the fire breached a 3 m wide mineral earth track and burnt into two-year-old fuel in the buffer strips for a distance of up to 40 m on a front about 80 m wide. Plate 15 shows the behaviour of the head fire in Plot D as it approached and breached the track at the southern end of the plot. The subsequent extent of fire spread and fuel consumption in the buffer strip is illustrated in Plate 16.

Plate 12 Low intensity fire burning in Plot O under dry conditions (M_{ls} of 4 per cent) with light and variable winds ($U_{10} < 1.5$ m s^{-1}). Note that the flame front is continuous even in areas of sparse fuel. Flames are mostly vertical and about 1 m long.

Plate 13 Black and white infrared photograph showing the main fire front in Plot D between 4 and 5 minutes after the start of ignition. This photograph was taken from the top of an 8 m tall tower. Direction of fire spread is from north (right) to south (left).

Plate 14 Photograph showing the main fire front in Plot D between 4 and 5 minutes after the start of ignition, taken from gound level at the same point as Plate 13. The target visible at left is 4 m tall.

Plate 15 Experimental fire in Plot D breaching the 3 m wide mineral earth track at the southern end of the plot. Wind speed (U_{10}) at the time was 6.5 m s^{-1}. The clump of mallee at the right of the photograph is about 4 m tall.

Plate 16 Photograph showing the extent to which the fire from Plot D consumed the two-year-old fuel in the adjacent scrub-rolled buffer strip.

The fire from Plot G also burnt across a track on a front of about 100 m wide but only spread about 10 m into the two-year-old fuel in the buffer strip. Stronger winds at the time of the fire in Plot D were probably the reason for the extent of fire spread in the two-year-old fuel being greater for Plot D than for Plot G.

4.5.12 Fuel consumption

For the purpose of examining fuel consumption experimental fires were grouped into three categories based on the pattern of fire spread within plots. Categories of fire spread, corresponding to those described in Section 4.5.2, were as follows:

- uniform - fires that burnt out at least 75 per cent of the plot following the initial ignition and did not require any further lighting;

- conditional - fires that burnt less than 75 per cent of the plot following initial ignition but that spread freely following subsequent ignition(s) when the wind direction was more perpendicular to the ignition line;

- non-sustaining - fires that did not spread extensively following initial or subsequent ignitions because of unfavourable burning conditions.

Plot C contained two distinct fuel types in which the fire behaved quite differently, and fuel consumption in this plot was therefore analysed separately from the other plots. None of the grid points in Plots Q and R were burnt and so these plots were not included in the analysis of fuel consumption.

Plots allocated to the uniform fire spread category exhibited high levels of consumption for litter, elevated dead and live fuel fractions (Fig 4. 13). At those points which did burn more than 80 per cent of litter was consumed. Typically, dead elevated fuel within a particular height class either remained unburnt or was almost entirely consumed. The proportion of points at which elevated dead fuel was consumed decreased progressively with height above ground, with about 80 per cent of points in the 0-0.4 m height class burnt but only 50 per cent of points in the >2 m height class burnt. Live fuel up to 5 mm in diameter was consumed in all height classes in uniformly burnt plots, but the proportion of points at which live fuel was burnt decreased with increasing height above ground. For live fuel the modal diameter consumed declined from 3 mm in the 0-0.4 m height class to 2 mm in the >2 m height class.

The estimated average fuel consumption for fires in the uniform spread category was 1.15 kg m^{-2}. This consisted of 0.48 kg m^{-2} of litter, 0.25 kg m^{-2} of elevated dead fuel and 0.41 kg m^{-2} of live fuel. The proportion of the fuel load in each height stratum regarded as available fine fuel (dead <6 mm diameter, and live leaves and twigs <4 mm) was taken into account in calculating this average value, and it was assumed that all litter was consumed.

In the case of plots allocated to the conditional fire spread category a substantial proportion (>25 per cent) of all fuel fractions remained unburnt following the initial ignition. However, after subsequent ignition(s) the extent of fuel consumption in plots in the conditional spread category became much the same as that of plots in the uniform spread category (Figure 4. 13). The proportion of litter consumed generally exceeded 80 per cent, both at those points burnt following the initial ignition and at those burnt as a result of subsequent ignitions. Consumption of dead and live elevated fuel declined with increasing height above ground. Within a given height class dead fuel tended to either remain unburnt or have been fully consumed.

The pattern of litter fuel consumption for fires in the non-sustaining category contrasted strongly with that observed for uniform and conditional spread fires (Figure 4. 13). Much of the area remained unburnt even following several attempted ignitions, and consumption of the litter layer tended to be incomplete even at those points which did burn. This finding is consistent with the fragemented nature of the flame fronts observed in the fires that were categorised as non-sustaining. With the exception of the 0-0.4 m height class, very little elevated dead or live fuel was consumed by non-sustaining fires, and no live fuel >2 mm diameter was consumed.

The pattern of consumption of litter and elevated live and dead fuel fractions in the 0-0.4 m height class is illustrated for Plot C in Figure 4.14. There was almost complete consumption of litter fuel at the 12 sample points in the mallee-heath vegetation, whereas nine of the 12 sample points in the swamp vegetation remained unburnt; litter consumption at the three burnt plots varied between 40 per cent and 90 per cent. The extent of consumption of elevated dead and live fuel above 0.4 m height in the mallee-heath vegetation was similar to that of plots in the uniform and conditional spread categories.

4.5.13 Calculation of frontal fire intensity

Frontal fire intensities (Byram 1959) were calculated for the nine plots for which reliable estimates of forward rate of spread were available using the formula:

$$I = h \; w \; R$$

where I is fire intensity in kW m^{-1}, h is the fuel low heat of combustion in kJ kg^{-1}, w is the fuel load consumed in kg m^{-2}, and R is the rate of spread of the fire in m s^{-1}. Fuel low heat of combustion was set at 18 700 kJ kg^{-1} with a reduction of 24 kJ kg^{-1} for each percentage point of moisture content in the deep litter fuel. These values were taken from Alexander (1982) as specific values for common shrubs and eucalypts in mallee-heath were not available. Consistent with the recommendation of Alexander (1982) no correction was made for radiation loss. Fuel load, w, was held constant at 1.15 kg m^{-2} (see Section 4.5.12) because specific values were not available for all experimental fires. Intensities were calculated for the average rate of spread, R, within the plot.

Calculated frontal fire intensities ranged from a minimum of 2705 kW m^{-1} for Plot H, the slowest spreading fire, to a maximum of 14290 kW m^{-1} for Plot D, the fastest spreading fire. Six plots (A, D, G, J, K and P) had average intensities exceeding 7000 kW m^{-1} which places them in the Very High intensity class defined by Cheney (1981). Two plots (E and O) were rated as High intensity (3000-7000 kW m^{-1}) while Plot H was rated as Moderate intensity (500-3000 kW m^{-1}). These values represent average intensities for each plot. Within each plot, fire intensity would have varied substantially as a result of localised variation in the rate of spread of the fire front and in the amount of fuel consumed. Relationships between fire intensity and flame dimensions are examined further in Chapter 5.

4.6 Validation of the mallee-heath fire spread model against independent observations

Predictions from the fire spread model developed from the experimental data were compared with rates of spread observed on an independent sample of five fires which burnt in mallee-heath or similar open shrubland. Details of the location, burning conditions and behaviour of these fires are provided in Table 4. 9. Two of these fires burnt in mallee-heath at the Stirling Ranges, while a third fire burnt in open shrubland at the Tutanning Nature Reserve which is in the central Western Australian Wheatbelt, about 250 km north of the Stirling Range. Fire spread observations were also available from two wildfires in the Fitzgerald River National Park, about 150 km east of the Stirling Range. McCaw *et al.* (1992) documented the behaviour of the 1989 Fitzgerald River fires which burnt during extreme weather conditions (Appendix D). An important criterion in selecting these particular fires for validation of the model was that wind speed and fuel moisture content had been measured at the time or could be estimated with reasonable accuracy from prevailing weather conditions. Each of the fires used for validation purposes was spreading on a relatively broad front (> 150 m) at the time that the rate of spread was determined. Spread rates for the three wildfires (Fires 2, 4 and 5) were averaged over relatively long periods (> 45 minutes); observations of prescribed fires were taken over short periods after the fires had appeared to reach a quasi-steady rate of spread.

TABLE 4.9

Details of five fires used for independent validation of the mallee-heath fire spread model. Dead fuel moisture content and wind speed values shown in brackets are best estimates; other data were measured on site.

Attribute	Fire 1	Fire 2	Fire 3	Fire 4	Fire 5
Fire type:	prescribed fire	wildfire Albany #2/87	prescribed fire	wildfire Albany #8/89	wildfire Albany #8/97
Location:	Stirling Range National Park:	Stirling Range National Park:	Tutanning Nature Reserve	Fitzgerald River National Park	Fitzgerald River National Park
Lat/Long:	34° 31’ S, 118° 13’ E	34° 30’ S, 118° 11’ E	32° 31’ S, 117° 23’ E	33° 55’ S, 119° 39’ E	33° 56’ S, 119° 50’ E
Fuel type:	mallee-heath	mallee-heath	open shrubland	mallee-heath	mallee-heath
Date of fire	6 Nov 1989	28 Oct 1987	20 April 1990	21 Dec 1989	27 Dec 1997
Duration of observation period	2 minutes	110 minutes	1 minute	45 minutes (1040-1125 hrs)	140 minutes (1725-1945 hrs)
Air temperature (°C):	20	30	25	35	26-30
Relative humidty (%)	48	20	45	9	40-50
Dead fuel moisture content (%)	9	(7)	7	(3)	(5)
U_2 (m s^{-1})	3.6	(3.0)	2.5	(8.0)	(6.0)
R (m s^{-1})	0.39	0.45	0.30	1.1	1.1

There was good agreement between predicted and observed rates of spread for four fires (Figure 4. 15). However, the rate of spread predicted by the mallee-heath model for Fire #4 at the Fitzgerald River was about one third greater than that estimated from field observations. Observed rates of spread were within the 90 per cent prediction limits determined for the mallee-heath fire spread model.

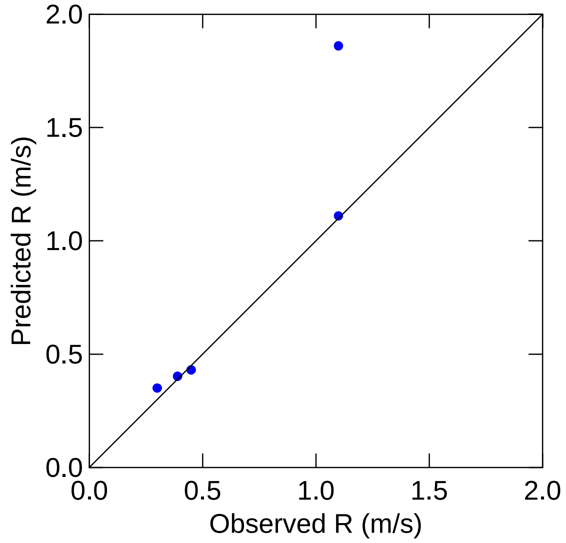


Figure 4. 15 Predicted versus observed *R* for independent mallee-heath fires detailed in Table 4.9.

4.7 Discussion

4.7.1 Threshold conditions for fires to sustain in mallee-heath

To predict fire spread in mallee-heath a determination must first be made as to whether a fire is likely to sustain under the prevailing environmental and fuel moisture conditions. Evidence from the experimental fires at the Stirling Range clearly indicates that it is the dryness of dead fuels, and in particular the shallow litter beneath the low shrubs, that most strongly affects the likelihood of a fire sustaining. The critical threshold of fuel dryness required for fire to sustain in mallee-heath was a moisture content of 8 per cent or less in the shallow litter layer. When the shallow litter was 8 per cent or drier, flames sustained even in the sparse litter fuel beneath the low shrub layer and fires maintained a continuous front, as in the case of the experimental fires in Plots H and O (Plates 11 & 12). Fires were therefore able to spread between the patches of continuous litter which tended to occur beneath clumps of mallee and some species of taller shrubs (see Section 2.5.4). As the moisture content increased above this threshold, fires were less likely to sustain in areas of sparse litter cover and flame fronts became fragmented, with almost no spread occurring once M_{ls} was 14 per cent or above.

The existence of a distinct threshold level of dead fuel moisture content necessary for continuous fire spread provides a plausible explanation for the sudden transitions in fire behaviour that have been observed to be a characteristic feature of fires in mallee-heath in southern Western Australia (McCaw *et al.* 1992). Transitions in fire behaviour are likely to reflect changes in the moisture content of the shallow litter which occur in response to changing environmental conditions, notably air temperature, relative humidity and solar radiation (see Chapter 3). Experimental results indicated that solar radiation can have an important influence on dead fuel moisture content and hence fire behaviour. This finding is consistent with investigations by Byram and Jemison (1943) and Van Wagner (1969) who developed algorithms to describe the effect of radiation on fuel surface temperature. Countryman (1977) also identified the strong dependence of litter moisture on radiation effects, particularly in vegetation types which vary widely in crown density and the amount of shading provided to the ground surface. The need to consider fuel temperature and solar heating effects on fire behaviour has been strongly advocated by Campbell *et al*. (1994) for chaparral shrublands in southern California.

The extent to which strong winds can offset the controlling effect of fuel moisture on fire spread in mallee-heath appears to be quite limited, although further observations from fires burning under stronger winds (U_2 >4 m s^{-1}) at marginal levels of fuel dryness (M_{ls} 9-12 per cent) are required to confirm this conclusion. Threshold burning conditions are likely to vary according to the characteristics of the fuel bed, and will be linked to the age and species composition of the vegetation (Chapter 2). The loading and cover of litter will be lower in younger vegetation, and in vegetation that lacks a layer of mallee eucalypts and tall shrubs. Observations of experimental fires indicated that very dry conditions and strong winds were necessary for fires to spread in highly discontinuous fuels. This was clearly illustrated in the case of Plot C where the fire failed to spread into the central part of the plot where the shrub and litter fuels were much more discontinous than those in the surrounding areas of mallee-heath. The fire extinguished even though dead fuels were dry enough to sustain fire elsewhere (M_{ls} = 7 per cent). Similarly, even the most intense experimental fires (Plots D and G) failed to spread in the sparse two-year-old vegetation in the buffer strips adjacent to the plots.

The observation that burning conditions must reach certain critical thresholds before fires will sustain has been made for a number of other discontinuous fuel types. Well documented examples include hummock grasslands in the Australian arid zone (Burrows *et al.* 1991, Gill *et al.* 1995), and oak-chaparral shrublands and pinyon-juniper woodlands in the western United States (Lindenmuth and Davis 1973, Bruner and Klebenow 1979). Burrows *et al.* (1991) identified a critical range of wind speed (U_2 of 3.3-4.7 m s^{-1}) necessary for fires to spread in hummock grasslands of spinifex (*Triodia basedowii* and *Plechtrachne schinzii*) in the Gibson Desert of Western Australia, and reported that this threshold was unaffected by fuel dryness up to a moisture content level of 30 per cent. The dominant effect of wind on fire spread in hummock grasslands has been attributed to the horizontal discontinuity of the fuel bed which consists of discrete hummocks separated by expanses of bare ground. For fires to spread in such discrete fuels the wind must be sufficiently strong to tilt flames across to the next hummock for long enough to ignite it (Gill *et al.* 1995). Threshold wind speeds for continuous fire spread are therefore likely to vary according to the size, shape, condition and spatial distribution of hummocks (Bradstock and Gill 1993). Gill *et al*. (1995) noted that an initiation-of-spread analysis should be included in any fire spread prediction system developed for hummock grasslands.

Marsden-Smedley *et al*. (1998) analysed data from 156 fires in Tasmanian buttongrass moorland using logistic regression and classification tree techniques to identify conditions under which fires would self extinguish. Similar analytical techniques could be employed for mallee-heath but the number of experimental fires would need to be expanded beyond that available in the present study.

For oak-chaparral shrubland Lindenmuth and Davis (1973) noted that 'people experienced in Arizona chaparral have always maintained that chaparral either burns fiercely or does not burn at all - no gradation in between'. Experimental burning studies by Lindenmuth and Davis confirmed this rule of thumb and identified a critical rate of spread of about 0.1 m s^{-1} . In oak chaparral, burning conditions had to be sufficent to generate spread at or above that level before fires would spread across country. Wind speeds (U_{10}) of 3.6 to 4.2 m s^{-1} were required for satisfactory fire spread during favourable temperature and fuel moisture conditions, but strong winds did not compensate for otherwise unfavourable conditions. This behaviour appears somewhat similar to the situation in mallee-heath. Based on the descriptive account of fuel characteristics in their paper and my field observations of oak-chaparral it seems that individual oak clumps are relatively discrete and that this fuel type is more discontinous than mallee-heath, probably being intermediate between mallee-heath and hummock grassland.

Bruner and Klebenow (1979) found that the likelihood of a fire sustaining in pinyon-juniper woodland could be predicted from a simple score comprising the wind speed, air temperature and percentage vegetation cover; the height at which wind speeds were measured was not, however, specified in their paper. While having some application in localised situations this approach has the limitations of not identifying the relative importance of the various factors contributing to the score, and not indicating potential forward rate of spread, and hence fireline intensity. Such an approach would be unlikely to succeed in mallee-heath because strong winds do not appear to compensate sufficiently to offset moist litter fuels.

4.7.2 Factors affecting rate of spread in mallee-heath

Wind speed was found to be the dominant factor affecting the forward rate of spread in mallee-heath, accounting for 72 per cent of variation in rate of spread when fitted as a power function of U_2. The dominant effect of wind speed on rate of spread has been reported for a range of fuel types including eucalypt forest (Cheney *et al*. 1992, Burrows 1994), grassland (Cheney *et al*. 1993) and buttongrass moorland (Marsden-Smedley and Catchpole 1995b). Power functions have been used to describe the effect of wind speed on rate of spread in each of these fuel types, with the value of the exponent used varying from 0.61 in regrowth *Eucalyptus sieberi* forest (Cheney *et al*. 1992) up to 2.67 in *Eucalyptus marginata* forest (Burrows 1994). Marsden-Smedley and Catchpole (1995b) used an exponent of 1.31 for buttongrass moorland, but noted that their choice of equation had been influenced by rate of spread observations from two high intensity wildfires. The value of the exponent reduced to 0.88 if only the experimental moorland fire data were included in their model. Exponents fitted to data for mallee-heath (this study) and grassland (Cheney *et al*. 1993) were both close to unity, suggesting an almost linear relationship between wind speed and rate of spread in these open vegetation types. The effect of wind speed on rate of spread is also treated as a linear function in the gorse and heather model of Thomas (1971) and the oak chaparral model of Lindenmuth and Davis (1973), although the latter model includes only a relatively weak wind speed effect.

There was some evidence that the model based on a power function of wind speed may overpredict the rate of spread of mallee-heath fires burning in very dry fuels when U_2 is 8 m s^{-1} or greater. However, the extent of the overprediction was only of the order of 30 per cent and the predictions were within the 90 per cent limits established for the model. Some of the prediction error could be the result of using model inputs that were not truly representative of the conditions acting on the fire. In the case of the observations from the Fitzgerald River wildfires, use of an inappropriate wind speed is the most likely source of error in model predictions. Other factors that may account for differences between predicted and observed rates of spread include uncertainty in estimating the actual rate of spread of the fire, and differences in the vegetation and fuel. Legislation and safety considerations make it impractical to conduct experimental burning under conditions that approach the severity of burning conditions experienced in the Fitzgerald River wildfires, and refinement of the mallee-heath fire spread model for severe burning conditions will therefore depend on gathering further data from well-documented wildfires. Any tendency for the mallee-heath model to overpredict the rate of spread under more severe burning conditions will provide a margin of safety when the model is employed to predict the spread of wildfires. This is preferable to underprediction of fire behaviour which may result in decisions being made which place firefighters and the general community at risk.

A theoretical objection may be raised against a fire spread model based on a power function of wind speed as it predicts zero spread rate under still conditions when in fact field observations confirmed that flames did spread, albeit slowly. This is of little consequence from a practical standpoint as the rate of spread and intensity of mallee-heath fires is negligible during still conditions. Under still conditions fires would be unable to cross tracks or substantial areas of bare ground and could easily be controlled by direct attack.

Functions based on an exponential relationship between wind speed and rate of spread have also been fitted to experimental data for grasslands (McArthur 1966, 1977) and eucalypt forests (McArthur 1962, 1967, Beggs 1976). Cheney (1981) noted that, at relatively low wind speeds, a variety of curvilinear relationships could be assigned constants which result in similar curve shapes but that the functions diverged widely when extrapolated to high wind speeds. Burrows (1994) evaluated a model for fire spread in *E. marginata* forest which employed an exponential function of wind speed, but concluded that the model predicted unrealistically high rates of spread for in-forest wind speeds above about 4 m s^{-1}. This conclusion was based on an examination of rates of spread from well documented wildfires burning under severe weather conditions.

Dead fuel moisture content affected both the likelihood of a fire sustaining, and the resulting rate of spread. The presence of moisture in fuel affects several important aspects of the combustion process including the extent of fuel consumption in the flaming zone, the evolution of smoke and the rate of combustion (Pompe and Vines 1966). Moist fuels burn more slowly than dry fuels and produce greater amounts of smoke, with Pompe and Vines (1966) noting that burning eucalypt litter with a moisture content of 10 per cent produced substantially more smoke than did oven dry leaves, particularly during the early stages of combustion. Fuel moisture may also affect the efficiency of radiative heat transfer during a fire by reducing the emmisivity of flames (King 1973, Vines 1981). From the point of view of the fire spread mechanism in mallee-heath, an important role of the deep litter layer may be to increase the intensity of the fire and the likelihood of flames extending into the foliage of the taller shrubs and mallee eucalypts where the windfield is stronger. Variables which included the moisture content of the deep litter layer in mallee-heath explained a greater proportion of variance in rate of spread than did those based on the moisture content of the shallow litter or the dead components of the elevated fuel. Prior rainfall effects are likely to be reflected in the moisture content of the deep litter for a considerably longer period than will be the case for the shallow litter or the elevated dead fuel. The moisture damping coefficient included in the fire spread model for mallee-heath (-0.11) was similar to that used for grassland (-0.09) by Cheney *et al*. (1993) but considerably more than the coefficient of -0.02 included in the buttongrass moorland model of Marsden-Smedley and Catchpole (1995b).

There was no evidence of a relationship between rate of spread and live shrub foliage moisture content or indices of seasonal drought. The absence of correlations with drought indices is not altogether surprising as there is no obvious mechanism by which mallee-heath might become more flammable as the dryness of the soil increased. This contrasts with the situation in vegetation types with a substantial component of annual grasses which cure progressively as the summer advances, or in forest types with deep organic layers which require protracted periods of dry weather to become dry enough to carry fire. A study of shrub foliage moisture contents (Section 3.4) revealed little variation throughout the year and no relationship between foliage moisture content and calculated drought indices.

The experimental site comprised a single fuel age class and had been deliberately selected to maximise the uniformity of the vegetation within the plots. Identification of any effect on rate of spread attributable to between-plot variation in fuel attributes was probably precluded by the relatively small number of fires available for use in the rate of spread analysis. Thus, percentage cover of mallee within individual plots had no detectable effect on rate of spread. Similarly, no attempt was made to investigate the effect of variation in fuel loading on rate of spread, even though fuel loading has been included in a number of fire spread models (see Sections 2.2 and 4.2). This question is currently being addressed for dry euclaypt forest by means of an extensive program of simultaneous experimental fires in fuels of varying time since fire (Cheney *et al*. 1996)

The absence of a clear trend of increasing rate of spread with time since ignition suggests that the build-up time (Cheney and Gould 1997) of experimental fires was quite short. Measured rates of spread could therefore be considered to represent a quasi-steady state determined largely by the wind speed and fuel moisture conditions. The good agreement found between predictions from the mallee-heath model and observations from larger scale fires lends further support to this proposition. Cheney and Gould (1997) analysed the spread of a large number of experimental grass fires of varying sizes and concluded that the width of headfire required to attain a quasi-steady rate of spread depended on wind speed. When U_2 was 3 m s^{-1} the width of headfire required to attain a rate of spread within 10 per cent of the quasi-steady state was about 70 m in open grassland and almost 200 m in grassy woodland. The use of 200 m line ignitions for the experimental fires in mallee-heath is likely to have minimised the build-up time of the fires. For six of the experimental fires (Plots D, G, H, J, O and P) the direction of spread was generally purpendicular to the ignited edge of the plot, and the effective length of ignition line was therefore close to 200 m. The effective ignition line length in Plots A, E and K was considerably less than 200 m because the prevailing winds resulted in fires which spread diagonally across the plots. Despite having narrower headfires these three fires did not appear as outliers the rate of spread analyses.

Experimental fires burning under summer conditions had rates of spread up to 0.67 m s^{-1}, frontal fire intensities up to 14 000 kW m^{-1} and flames up to an average length of 11 m. Fires of this severity have seldom been achieved in the context of experimental studies. Some of the most intense experimental fires reported in the literature are those of Van Wilgen (1984) in South African fynbos shrubland which achieved peak intensities of 21 000 kW m^{-1}. The experimental grass fires conducted in the Northern Territory by Cheney *et al*. (1993) attained similar maximum intensites to the mallee-heath fires at the Stirling Range, although this was achieved through a combination of considerably higher spread rates in grass swards that averaged one quarter to one third of the fuel loading of mallee-heath.

It would not have been possible to conduct experimental fires of high to very high intensity in mallee-heath without the network of scrub-rolled and burnt buffer strips established beforehand. The substantial cost associated with establishing plots and buffer strips restricted the number of plots that could be established with the resources available for the project. Buffer strips also occupied additional land area within the experimental site. The Stirling Range experimental site could not have been increased in size without encompassing structurally different vegetation types, thereby introducing a substantial component of between-plot variation in fuel characteristics. For future studies of fire behaviour in fuel types which are known to have distinct threshold conditions required for fire spread there would be merit in establishing plots of several different sizes. Small plots could be ignited under conditions that were considered to be marginal for fire spread while larger plots could be retained for burning under conditions where fire spread was likely to occur. Such an approach would allow more experimental fires to be conducted within a given area of land, and has been recommended by Alexander and Quintilio (1990). Experimenters would, however, need to be aware of possible interactions between the length of ignition line, the probability of fire spread and the resulting rate of spread.

4.8 Conclusions

Prediction of fire spread in mallee-heath requires two distinct steps: the first step is to determine whether or not a fire will sustain under the prevailing environmental and fuel moisture conditions; the second step is to predict the forward rate of spread of the fire. Experimental fires sustained in mature mallee-heath when the moisture content of the shallow litter beneath the low shrubs was below 8 per cent. This threshold level of fuel dryness allowed fires to maintain a continuous front in the sparse fuels that occured between clumps of mallee and taller shrubs. Forward rate of spread of experimental fires was modelled as a function of the wind speed in the open (U_2), and the moisture content of the deep litter beneath mallee clumps. The fitted model accounted for 84 per cent of variation in the rate of spread of experimental fires. Under summer burning conditions, experimental fires had rates of spread up to 0.67 m s^{-1}, frontal fire intensities up to 14 000 kW m^{-1} and flames up to an average length of 11 m. Fires of this severity have rarely been achieved in the context of experimental studies. Comparison with spread observations from a limited number of prescribed and wild fires indicates that the mallee-heath fire spread model developed from experimental data provides robust predictions over a broad range of burning conditions. Every opportunity should be taken to gather additional fire spread observations from wildfires so that the predictive capability of the model can be further tested for fires burning under severe weather conditions.

CHAPTER 5

COMPARISON OF FIRE BEHAVIOUR IN MALLEE-HEATH WITH FIRE DANGER INDICES AND PREDICTIONS FROM FIRE BEHAVIOUR MODELS

5.1 Introduction

This chapter examines the observed behaviour of fires in mallee-heath in relation to fire danger indices that are commonly used for fire danger rating purposes in Australia, and in relation to predicted rates of spread for a number of other shrubland vegetation types.

Fire danger rating systems are important decision-making tools for land management agencies and fire authorities. Uses of a fire danger rating system include setting levels of preparedness for personnel and equipment, determining the type and frequency of fire detection observations, issue of public warnings, and enforcement of bans on the lighting of fires for management or recreation purposes (Luke and McArthur 1978, Cheney *et al*. 1990). Fire danger rating systems also provide an appropriate scale for management, research and the law for fire related matters. In Australia, fire danger has been directly related to the forward rate of spread of a fire burning in a standard fuel type. This approach has developed directly from the pioneering fire behaviour research of Alan McArthur and George Peet during the late 1950’s and the 1960’s, as described by Cheney (1991). Temperate grasslands and open eucalypt forests have been adopted as the standard fuel types for fire danger rating because these vegetation types are both prone to fire and widespread throughout southern Australia. Much of the landscape across substantial areas of semi-arid southern Australia has been developed for agriculture and now comprises a mosaic of introduced pasture grasses and annual crops such as wheat, interspersed with remnants of woodland, mallee and other shrubland communities. There is evidence to suggest that under some circumstances, fire danger rating systems developed for grassland and open eucalypt forest may not adequately describe the fire danger in mallee vegetation (Jones 1973 &1974, Billing 1981, Rawson 1981, Cheney *et al*. 1990). An important aim of the work described in this chapter is to determine whether existing fire danger rating systems adequately reflect potential fire behaviour and difficulty of suppression in mallee-heath fuel types. Rate of spread was considered the best index of fire behaviour and difficulty of suppression for such an analysis because it is the primary output from most fire danger rating sytems and fire behaviour prediction models, and because it is directly related to other important fire behaviour characteristics including intensity and flame dimensions (Sections 4.5.11 and 4.5.14).

Emprical fire behaviour models have been developed for a number of shrubland fuel types, including several that have a similar vegetation structure to mallee-heath. Aspects of the development, structure and performance of these models have been reviewed in Section 4.2. If fires in mallee-heath behave similarly to fires in other shrubland fuel types, then development of a generic shrubland fire spread model from empirical data could prove feasible. A generic fire behaviour model could provide an improved basis for fire danger rating in shrubland areas, and could potentially alleviate the need to develop specific models to predict fire behaviour in different shrub communities.

Fire behaviour predictions can also be made for a specific fuel types using Rothermel's (1972) fire spread model. The BEHAVE sytem (Burgan and Rothermel 1984, Andrews 1986) provides a readily available procedure for developing customised fuel models with appropriate fuel parameters which can subsequently be used in conjunction with the Rothermel model. Predictions from the model apply to fires spreading through surface fuels up to about 2 m tall that are contiguous with the ground (Andrews 1986).

In addition to forward rate of spread, flame dimensions are an important descriptor of the behaviour, difficulty of suppression and ecological effects of fire. The relationship between flame length or flame height and fireline intensity has been investigated experimentally in several fuel types including pine litter with grass (Byram 1959), fynbos shrubland (Van Wilgen *et al*. 1985), buttongrass moorland (Marsden-Smedley and Catchpole 1995b) and open eucalypt forest (Burrows 1994). Nelson and Adkins (1986) conducted laboratory and field experiments in southern rough (a mixture of needle litter, palmetto (*Serenoa repens*) and low shrubs) and used the data to estimate fuel specific parameters for Byram's flame length model. Flame lengths in southern rough were only about 70-80 per cent of those predicted by the model. Experimental data were also used to calibrate a model for wind-blown flames developed by Albini (1981). Thomas (1963) investigated flame dimensions using combustion data gathered in laboratory studies, while more recently Weise and Biging (1996) have examined the combined effects of wind velocity and slope on flame dimensions for experimental fires conducted in a tilting wind tunnel. They also found that flame lengths were less than predicted by Byram's (1959) model. Most experimental data for flame dimensions have been obtained from fires with frontal intensities below 3000 kW m^{-1}, although the data set of Marsden-Smedley and Catchpole (1995b) includes fires up to about 6000 kW m^{-1}. Descriptive classifications of fire behaviour developed for particular fuel types generally indicate the range of flame height or flame length expected for various fire danger classes (Cheney 1981, Burrows 1984, Alexander and De Groot 1988, Alexander and Lanoville 1989), and some fire behaviour guides permit prediction of flame dimensions according to the burning conditions (McArthur 1967, Rothermel 1983, Andrews 1986).

In subsequent sections of this chapter the rate of spread and flame dimensions observed during experimental fires at the Stirling Range study area and a number of other fires in mallee-heath are compared with predictions from a range of existing fire behaviour models.

5.2 Evaluation procedure

5.2.1 Rate of spread

Rates of spread of experimental and wild fires in mallee-heath were compared with predictions from four fire danger rating systems:

- the Mark IV Grassland Fire Danger Meter of McArthur (1966),
- the Mark V Forest Fire Danger Meter of McArthur (1967, 1973),
- the jarrah (*Eucalyptus marginata*) forest fire spread model presented by Burrows (1994),
- the Initial Spread Index from the Canadian Fire Weather Index system (Van Wagner 1987);

and fire spread predictions from four fire behaviour models applicable to shrubland fuel types:

- the gorse and heather model of Thomas (1971),
- the oak chaparral model of Lindenmuth and Davis (1973),
- the buttongrass moorland model of Marsden-Smedley and Catchpole (1995b),
- the fire spread model of Rothermel (1972) using a customised fuel model developed for mallee-heath, and the fynbos shrubland fuel model of Van Wilgen (1984).

Data from 14 experimental mallee-heath fires at the Stirling Range study site were used in the analysis; this included five fires which did not sustain. Four fires that sustained, but which did not have reliable estimates of rate of spread were not used in the analysis. Spread data from two prescribed fires and three wildfires in mallee-heath detailed in Table 4.9 were also compared with predictions from the various models. This latter group are referred to as validation fires. For those models requiring a direct measure of dead fuel moisture content, separate predictions were made using M_{ls}, which has been shown experimentally to be important in determining whether a fire will sustain, and M_{ld} which has been shown to have the greater effect on rate of spread than other dead fuel moisture variables (Sections 4.5.3 and 4.5.8). No measurement of M_{ld} was available for Plot L.

The goodness of fit was judged from inspection of scatterplots showing observed rates of spread against predicted values. Correlations between observed and predicted values were calculated for those models which displayed a superior fit. This information was supplemented by examination of the frequency distribution of under- and over-prediction scores using the procedure of Andrews (1980). Scores were calculated by dividing the absolute difference of the predicted and observed values by the larger of the two values, and multiplying by 100. An under-prediction score of 100 indicates that the fire was predicted not to spread, when in fact it did. An over-prediction score of 100 indicates that the fire was predicted to spread, but did not. Scores of 50 indicate that the prediction was either twice or half of the observed value. Gould (1991) employed this procedure in evaluating the goodness of fit of the Rothermel fire model to experimental grass fire data.

Procedures used to calculate fire danger indices and rates of spread from the respective models are described below:

McArthur Grassland and Forest Fire Danger Meters

The Grassland Fire Danger Meter (GFDM) provides the basis for fire danger rating in rural areas of Western Australia and several other States and Territories. The Forest Fire Danger Meter (FFDM), although not used for fire danger rating or fire behaviour prediction in Western Australia, is used routinely in regions of south-eastern Australia that contain extensive tracts of mallee shrubland. The extent to which these fire danger indices reflect potential fire behaviour and difficulty of suppression in mallee-heath fuels under particular burning conditions is therefore an important issue for fire authorities and rural fire fighters. Rates of forward spread for grassland and open eucalypt forest predicted by GFDM and FFDM respectively were determined using the equations fitted to McArthur's fire danger meters by Noble *et al*. (1980). Inputs were the measured values of T, RH and U_{10} for each fire (Table 4.1). Symbols are as used in previous chapters and defined in Appendix B. The predicted rate of spread from the FFDM was based on a fuel loading of 1.15 kg m^{-2} which is the average loading of fine fuel in 20-year-old mallee-heath (Section 2.5.2). The grass curing factor on the GFDM was held constant at 100 per cent, following the rationale that fires in mallee-heath mostly occur during summer and autumn when grass fuels are fully cured.

Jarrah forest fire danger

The jarrah forest Fire Danger Index (JFDI) represents the forward rate of spread of a fire burning on level terrain in open jarrah forest carrying standard fuel with a loading of 0.8 kg m^{-2}. Numerical values of the index indicate the rate of spread in units of metres per hour. Rate of spread is given as a function of wind speed in the forest at 1.5 m above ground (U) and the surface moisture content (SMC) of the litter layer by the equation of Burrows (1994):

$$\mathrm{JFDI} = 23.19\ \mathrm{SMC}^{-1.495}\ U^{2.674} + 11.6 \qquad (5.1)$$

The SMC is a percentage moisture content and U is in units of km h^{-1}. To predict rates of spread for mallee-heath fires, wind speeds at 10 m height in the open were converted to equivalent speeds at 2 m height inside standing vegetation using equation C5 (Appendix C). Rates of spread for mallee-heath fires were determined for three alternative measures of dead fuel moisture content: (a) M_{ls}, (b) M_{ld}, and (c) a predicted SMC based on antecedent weather conditions. The daily maximum SMC was calculated using the Forest Fire Behaviour Tables for Western Australia (Sneeuwjagt and Peet 1985) and then corrected to the time of ignition of each fire using the nomogram provided in the tables. Incomplete records prevented an SMC being calculated from antecedent weather for three of the validation fires.

Initial Spread Index

The Initial Spread Index (ISI) from the Canadian Fire Weather Index System accounts for the effect of wind speed and dead fuel moisture content on the rate of spread of a forest fire burning in litter fuel. The ISI for each fire was calculated using the tables for the Fire Weather Index System (Anonymous 1984). Inputs to the ISI are U_{10} and the Fine Fuel Moisture Code (FFMC). FFMC values corresponding to M_{ls} and M_{ld} for each fire were calculated according to the relationship described by Van Wagner (1987):

$$\text{FFMC} = 59.5\ (250 - M)/(147.2 + M) \qquad (5.2)$$

where M is the percentage moisture content of the fuel. The FFMC was also determined from antecedent weather conditions at the experimental site (rainfall, air temperature, relative humidity and wind speed at 1200 hours daily). Mr Liam Fogarty of the New Zealand Forest Research Institute at Rotorua kindly calculated the FFMC values from these data. Codes calculated from antecedent weather conditions were adjusted according to the time of ignition of the fire to which they corresponded. Incomplete records prevented an FFMC being calculated from antecedent weather for three of the validation fires.

Gorse and heather model

Thomas (1970, 1971) developed a fire spread model using data from experimental fires conducted in gorse and heather shrublands in southern England. This model related the rate of spread (R) to wind speed (U_2) and the fresh bulk density of the burnt fuel (ρ'_b) by the equation:

$$R\ \rho'_b = a\ (1 + U_2) \qquad (5.3)$$

Units are m s^{-1} for R and U_2 and kg m^{-3} for ρ'_b. The constant of proportionality, a, determined for Thomas's experimental data set was 0.07 kg m^{-3}. Rates of spread were predicted assuming an average ρ'_b of 1.42 kg m^{-3} for mallee-heath, which was derived using estimates of fuel consumption from experimental fires and a live fuel moisture of 85 per cent, this being a representative average value for mature foliage from mallee eucalypts and shrubs at the Stirling Range (Section 3.3).

Oak chaparral model

Lindenmuth and Davis (1973) developed an empirical model to predict the rate of spread in Arizona oak chaparral shrubland. Predictions from this model were made using the field workbook developed by Davis and Dieterich (1976) with T, RH, S and U as inputs. The model requires wind speeds measured at 20 feet (6.1 m) above the ground and so measured values of U_{10} were adjusted to 6.1 m equivalents using the Applied Meteorological Tables of Beer (1990). A roughness length of 0.2 m was assumed on the basis of typical values for shrubland vegetation provided in the tables. Foliar moisture content was held constant at 85 per cent, as already described. The model includes a chemical coefficient which accounts for the effect of phosphorous content on the flammability of chaparral foliage. Coefficient values vary from 1.0 to 2.2 depending on the amount and timing of precipitation and are greater during spring and early summer than during late summer and autumn, when they reduce to 1.0. The basic rate of spread determined from weather conditions and foliar moisture content is multiplied by the chemical coefficient to obtain the rate of spread on flat terrain. In view of the lack of information about the influence of foliar nutrients on fire behaviour in mallee-heath, the chemical coefficient was held constant at 1.0 which is typical of chaparral fuels under late summer and autumn conditions.

Buttongrass moorland model

Marsden-Smedley and Catchpole (1995b) developed an emprical model to predict the the rate of spread of fires in Tasmanian buttongrass moorlands. Data for the model came from experimental fires with 50 m or 100 m ignition line lengths lit in fuels ranging in age from four to 25 years since fire. Data from a number of prescribed hazard reduction fires and two high intensity wildfires were used used to develop the model. Headfire rate of spread in buttongrass moorland is predicted by the equation:

$$R = 0.678\ U^{1.312} \exp(-0.0243\ Mf_{dead})\ (1-\exp(-0.116\ Age)) \qquad (5.4)$$

where R is the rate of spread and U is the surface wind speed, both in units of m s^{-1}, Mf_{dead} is the percentage moisture content of the elevated dead fuel, and *Age* is the number of years since the last fire. Predictions for mallee-heath were based on measured values of U_2, M_{ls} and M_{ld} for each experimental fire. *Age* was held constant at 20 years on the basis that 20-year-old buttongrass moorland has a similar proportion of dead fuel to mallee-heath of the same age. In buttongrass moorlands the percentage of dead fuel at an age of 20 years varies from about 40 per cent on low productivity sites to 60 per cent on medium productivity sites. In 20-year-old mallee-heath, about 45 per cent of the elevated shrub fuel and about 60 per cent of the combined loading of litter and shrubs is dead (Section 2.5.3). Marsden-Smedley and Catchpole (1995b) remarked that the proportion of dead fuel appeared to have more effect on the rate of spread than did the total fuel loading.

Rothermel model with customised fuel parameters for mallee-heath and fynbos shrubland

Rate of spread predictions from Rothermel's (1972) fire behaviour model were made using the BEHAVE system (Burgan and Rothermel 1984, Andrews 1986). A customised mallee-heath fuel model was developed from fuel particle and fuel bed characteristics determined for 20-year-old mallee-heath using the methodology described in Chapter 2. Fuel loadings and surface area to volume ratios for different components of the stylised fuel bed are shown in Table 5.1. The surface area to volume ratio of fine dead fuels <6 mm diameter was determined as the weighted mean of litter components, calculated as $2/d$, and cylindrical stem components, calculated as $4/d$, where d is particle thickness. A mean thickness of 0.4 mm was assumed for leaves, based on measurements of a range of different plant species, and an average thickness of 3 mm assumed for other dead fine fuel particles. A similar procedure was employed to determine the surface area to volume ratio of live fine fuels <4 mm diameter which represent the component of the live fuel available for combustion. Fuel bed depth was set at 0.9 m which is the median height of live shrubs measured in 20-year-old mallee-heath. . The stylised fuel bed had a packing ratio of 0.00262. Separate rate of spread predictions were made for extinction moisture contents set of 10 per cent and 14 per cent to examine the sensivity of the model to this parameter. Evidence from experimental fires (Plot F in particular) showed that no fire spread was likely to occur once M_{ls} exceeded 14 per cent, and that fires were unlikely to maintain a continuous front at an M_{ls} of 9 per cent or greater. An extinction moisture content of 10 per cent was the lowest that could be set in the version of the BEHAVE computer package used to make the predictions. Mid-flame wind speed was approximated by U_2, 1 hour fuel moisture content by M_{ls} and 10 hour and 100 hour fuel moisture contents by M_{ld}. Fuel heat contents for mallee-heath shrubs were not measured in this study and no values were available in the literature. A heat content of 20 000 kJ kg^{-1} was chosen on the basis that similar values have been applied to shrubland fuels in other studies (Van Wilgen 1984, Marsden Smedley and Catchpole 1995a). This is consistent with the recommendation of Burgan and Rothermel (1984) that a heat content of 19 500-21800 kJ kg^{-1} be used for volatile fuels which burn vigourously when alive, such as chaparral shrubland.

Rate of spread predictions were also made using the stylised fuel model for fynbos shrubland developed by Van Wilgen (1984). Fuel loading and surface area to volume ratios for the various components of the fynbos fuel bed are shown in Table 5.1. Van Wilgen (1984) describes the methodology employed to derive values for fuel loading and surface area to volume ratio. Surface area to volume ratios given in imperial units in Table 4 of Van Wilgen's paper were divided by 0.3048 to obtain metric equivalents, in units of m^{-1}. The stylised fynbos model had a fuel bed depth of 0.91 m, a packing ratio of 0.00264, a heat content of 20 000 kW m^{-1}, and an extinction moisture content of 34 per cent.

TABLE 5.1

Loadings and surface area to volume ratios of fuel components in stylised fuel beds for mallee-heath (this study) and fynbos (Van Wilgen 1984).

Fuel component	Mallee-heath		Fynbos	
	Loading (kg m^{-2})	Surface area /volume ratio (m^{-1})	Loading (kg m^{-2})	Surface area /volume ratio (m^{-1})
Dead				
1 hour	0.74	3700	0.40	7200
10 hour	0.06	400	0.09	357
100 hour	-	-	0.01	100
Live				
Herbs	-		0.50	5900
Woody	0.41	3300	0.22	4900

5.2.2 Flame dimensions

Flame length observations from experimental fires were compared with predictions from the models proposed by Byram (1959), Thomas (1963), and Burrows (1994). Predictions from the flame height models of McArthur (1967), Nelson and Adkins (1986) and Marsden-Smedley and Catchpole (1995b) were also examined by correcting observed flame lengths to flame heights on the basis of average flame angles.

Details of models relating flame dimensions to fire intensity are provided in Table 5.2. Fire intensity (I_B) was determined using the procedure described in Section 4.5.13 using values of R appropriate to the location where flame dimensions were estimated, rather than the average value of R determined for the plot. Allowance was made for the quantity of fuel consumed by flames of different sizes, and for the moisture content of the dead fuel. Goodness of fit of flame predictions was evaluated using the same procedures as for rate of spread. Estimates of flame dimensions were not available for the four validation fires.

Flame height predictions for McArthur's (1967) Mark V Forest Fire Danger Meter were determined using a modified version of the equation fitted to the meter by Noble *et al*. (1980):

$$F_H = 46.8R + 2.4W - 2.0 \qquad (5.5)$$

where F_H is the flame height in m, R is the rate of spread in m s^{-1}, and W is the fuel load in kg m^{-2}.

TABLE 5.2

Models relating flame length F_L and flame height F_H, in metres, to Byram's (1959) fire intensity I_B , in kW m^{-1}. Other variables included in some models are surface wind speed U, in m s^{-1} and fuel heat content h, kJ kg^{-1}.

Source	Model	Fuel type
Bryam (1959)	$F_L = 0.0775\ I_B^{0.46}$	pine litter and grass
Burrows (1994)	$F_L = 0.0147\ I_B^{0.767}$	eucalypt forest litter
Thomas (1963)	$F_L = 18.6\ (I_B/h)^{2/3}$	laboratory and structural fires
Nelson and Adkins (1986)	$F_H = I_B/(360\ U)$	pine litter and palmetto
Marsden-Smedley and Catchpole (1995b)	$F_H = 0.148\ I_B^{0.403}$	buttongrass moorland

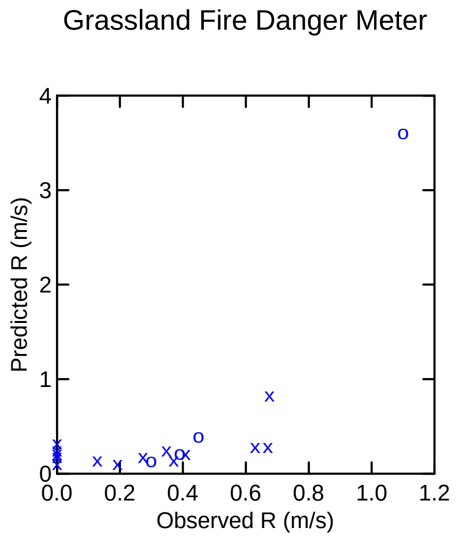
5. 3 Comparison of predicted and observed fire behaviour

5.3.1 Fire danger rating systems

Experimental fires were conducted at Grassland Fire Danger indices ranging from 3 (Low) to 23 (Very High) with corresponding forward rates of spread in grassland of 0.11 to 0.83 m s^{-1}. Three of the validation fires burnt under Low or Moderate fire danger conditions with predicted rates of spread in grassland of between 0.02 m s^{-1} and 0.09 m s^{-1} (Figure 5.1). The fourth validation fire had a predicted rate of spread of 3.6 m s^{-1} and burnt under Extreme fire danger conditions which exceeded the nominal upper limit of 100 for the GFDI. Rates of spread predicted by the Grassland meter were considerably lower than those observed for the mallee-heath fires, except for the experimental fire in Plot D which burnt during conditions of Very High fire danger, and the validation fire which burnt under Extreme fire danger conditions. The relationship between the rate of spread in grassland and the rate of spread in mallee-heath could not therefore be described by a simple linear function (Figure 5.1). Five experimental fires that failed to sustain had similar predicted rates of spread to fires that did sustain and spread. On this evidence, the GFDI does not appear suitable for defining threshold conditions required for sustained fire spread in mallee-heath, or for predicting the rate of spread.

Rates of spread predicted by the FFDM were much lower than those in mallee-heath, and did not exceed 0.30 m s^{-1} for any of the experimental or validation fires (Figure 5.1). The relationship between predicted and observed rates of spread was not consistent; some of the experimental fires that sustained had lower predicted rates of spread than fires which failed to sustain.

Rates of spread determined using the jarrah forest spread model and an SMC based on antecedent weather conditions were consistently lower than those determined using measured moisture contents, by as much as seven times in some cases (Figure 5.2). This was because dead fuels in mallee-heath were consistently drier than indicated by the SMC (refer to Chapter 3 for discussion of fuel moisture content in mallee-heath). The JFDI did not distinguish between fires that sustained and fires that did not sustain, regardless of which measure of dead fuel moisture content was used. Rates of spread in mallee-heath were substantially higher than predicted for jarrah on the basis of M_{ls}, except for the validation fire that burnt under extreme fire weather conditions which only spread at half the rate predicted for jarrah (Figure 5.2). The predicted rate of spread in jarrah fuels can be corrected for fuels that differ from the standard loading. Applying the appropriate correction factor from the FFBT for the amount of fuel consumed in mallee-heath would have increased predicted rates of spread by a constant factor of 1.3. Despite this correction, rates of spread predicted for jarrah forest remained an order of magnitude lower than in mallee-heath. The rate of spread in mallee-heath could not be related to the rates of spread predicted by the jarrah forest model and the FFDM using a simple linear function.



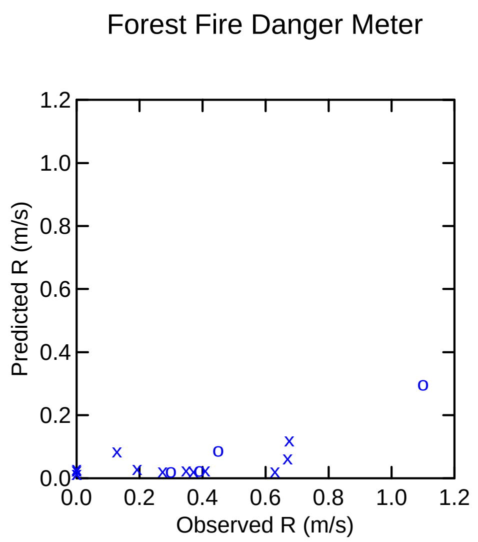


Figure 5.1 Comparison of predicted rates of spread from the McArthur Grassland and Forest Fire Danger Meters with observed rates of spread of mallee-heath fires. Experimental fires are indicated by crosses (x) and validation fires by circles (o). Note that the scales used on the vertical axis differ between graphs.

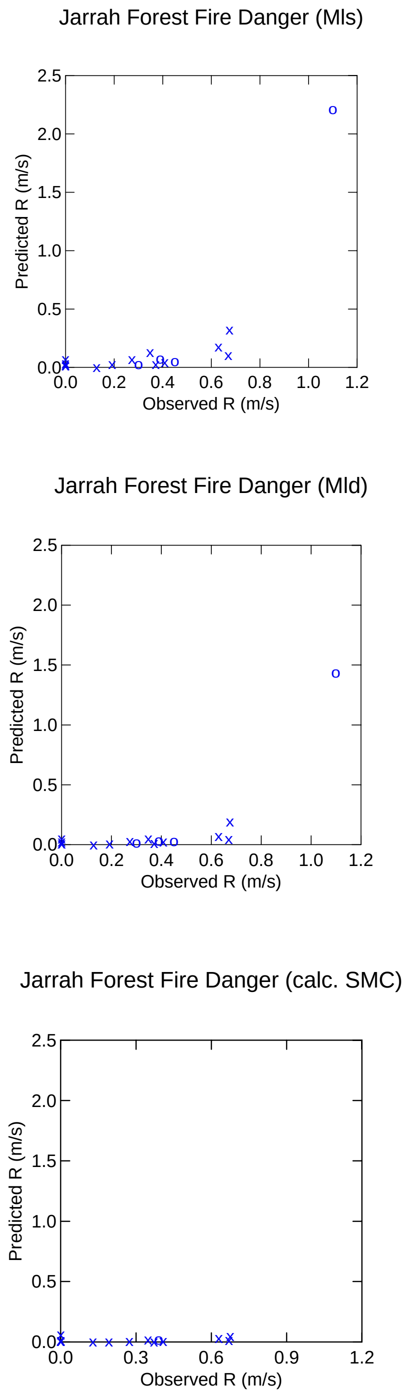


Figure 5.2 Comparison of predicted rates of spread for jarrah forest with observed rates of spread of mallee-heath fires. Experimental fires are indicated by crosses (x) and validation fires by circles (o). Rates of spread determined using SMC values based on M_{ls}, M_{ld} and an SMC calculated from antecedent weather are shown. fynbos model. Incomplete records prevented an SMC being calculated from antecedent weather for three of the validation fires.

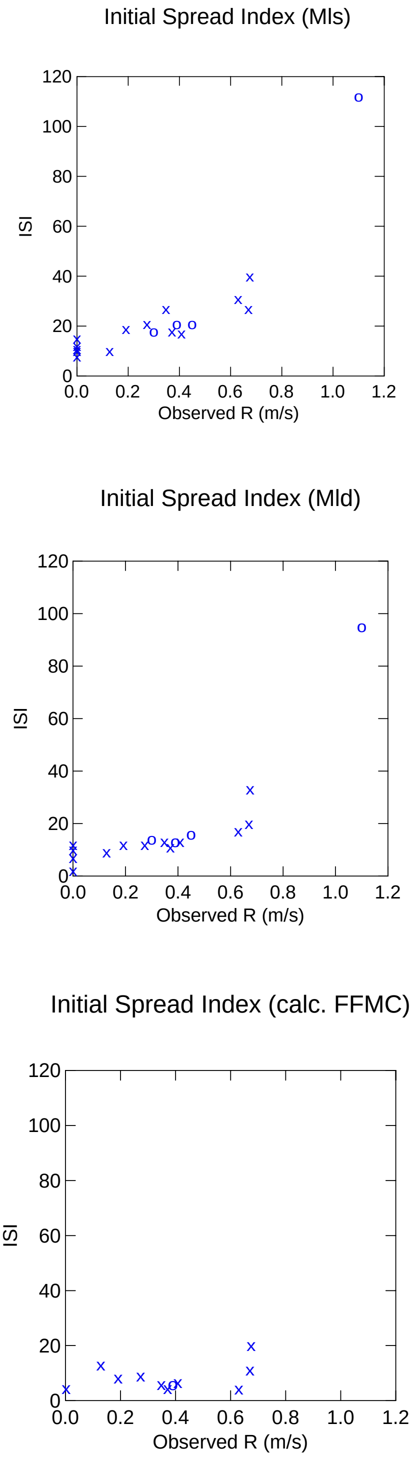


Figure 5.3. Comparison of the Initial Spread Index from the Canadian Fire Weather Index System with observed rates of spread of mallee-heath fires. Experimental fires are indicated by crosses (x) and validation fires by circles (o). Indices determined using FFMC values based on M_{ls}, M_{ld} and a FFMC calculated from antecedent weather are shown. Incomplete records prevented an SMC being calculated from antecedent weather for three of the validation fires.

The ISI determined using an FFMC based on records of antecedent weather showed no relationship with the rate of spread in mallee-heath, and did not provide any indication of whether or not a fire was likely to sustain (Figure 5.3) However, indices determined using an FFMC based on M_{ld} and M_{ls} did exhibit a clear relationship with the rate of spread in mallee-heath. This relationship was generally linear for rates of spread up to 0.7 m s^{-1} but tended towards an exponential form if the fastest spreading validation fire was taken into consideration. The five fires that did not sustain tended to be associated with low values of the ISI, the absolute value depending on which measure of dead fuel moisture content was used to determine the index.

5.3.2 Fire spread models

Rates of spread in mallee-heath were consistently higher than predicted by models developed for other shrubland fuel types, except for the fynbos shrubland which was predicted to spread faster than mallee-heath. Thomas's gorse and heather model consistently under-predicted the rate of spread in mallee-heath, and seven fires had under-prediction scores of between 50 and 75 indicating that predicted rates of spread were less than half those observed (Figure 5.4 and 5.5). There was a significant correlation ($r = 0.65$, $P = 0.04$) between the rate of spread predicted by Thomas's model and the observed rate of spread in mallee-heath, reflecting the almost linear dependence of mallee-heath rate of spread on wind speed (Section 4.5.7). Five fires had over-prediction scores of 100 indicating that the fires failed to spread (Figure 5.5).

The oak chaparral model predicted rates of spread in the range 0.05 to 0.13 m s^{-1} which was substantially less than observed for any of the mallee-heath fires. Fires that failed to sustain tended to have the lowest predicted rates of spread (<0.065 m s^{-1}), except for the fire in Plot A which did sustain and spread despite a predicted rate of spread of only 0.061 m s^{-1}. Rates of spread in mallee-heath were strongly correlated with predicted rates of spread in oak chaparral ($r = 0.834$, $P < 0.001$).

Rates of spread predicted by the buttongrass moorland model using M_{ls} were slightly faster (10-15 per cent) than those predicted using M_{ld}. The small difference in predicted rates of spread reflects the weak moisture damping effect in this model, and the relatively small difference between the two measures of fuel moisture content. The buttongrass model predicted rates of spread ranging from about 0.1 to 0.3 m s^{-1} for five fires that did not sustain (Figures 5.4). Fires in mallee-heath consistently spread faster than predicted by the buttongrass moorland model using either M_{ls} or M_{ld}, and seven fires had under-prediction scores of between 50 and 75 (Figures 5.5). The distribution of scores was the same regardless of whether predictions were based on M_{ls} or M_{ld}. Predicted rates of spread for buttongrass moorland were strongly correlated with observed rates of spread in mallee-heath (r =0.75 and 0.76 respectively, P < 0.01).

Rates of spread predicted by BEHAVE using with a customised fuel model for mallee-heath showed good agreement with observed values for the fires that did in fact spread (Figure 5.6), with the correlation coefficient being 0.93 (P<0.001) regardless of whether the extinction moisture content was 10 per cent or 14 per cent. Predictions made with an extinction moisture content of 10 per cent had lower mean absolute error (MAE) than those made with an extinction moisture content of 14 per cent for both the subset of fires that spread (MAE of 0.08 versus 0.10 respectively) and for all fires (MAE of 0.12 and 0.15 respectively). The number of fires that were predicted to spread but did not was reduced from four to two by using an extinction moisture content of 10 per cent instead of 14 per cent, and the resulting distribution of prediction scores was less skewed towards over-prediction (Figure 5.7).

Rates of spread predicted by BEHAVE for fynbos shrubland were faster than those observed for mallee-heath for all but the two slowest spreading experimental fires (Plots H and O), resulting in a pronounced skewness towards overprediction (Figure 5.7). However, there was a strong correlation (r = 0.91, P<0.001) between rates of spread predicted for fynbos and those observed in mallee-heath (Figure 5.6).

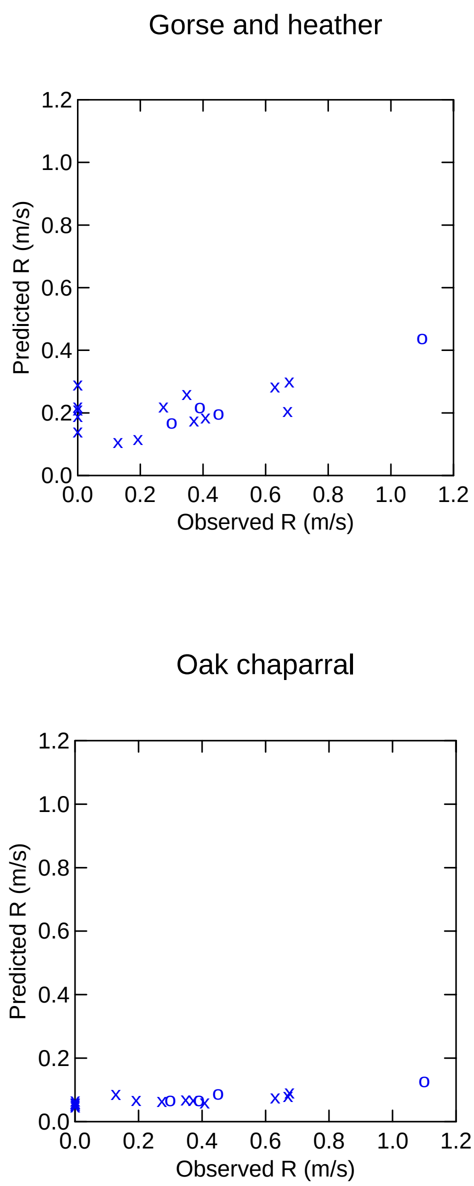
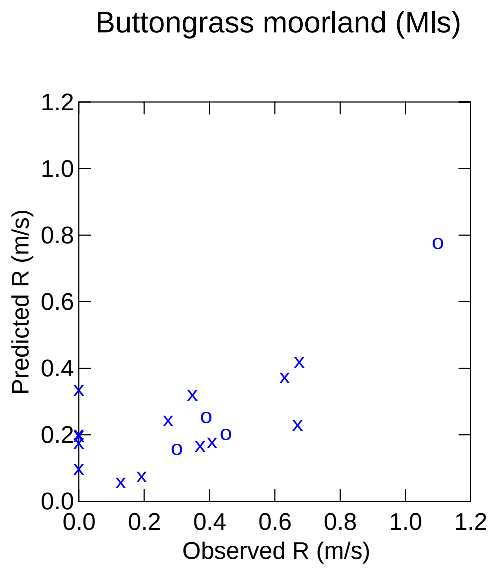
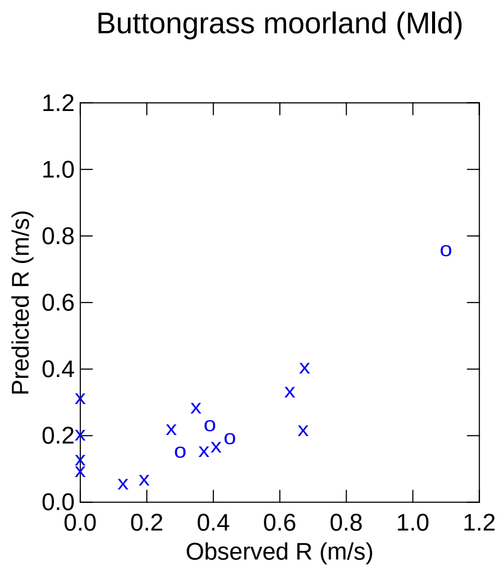
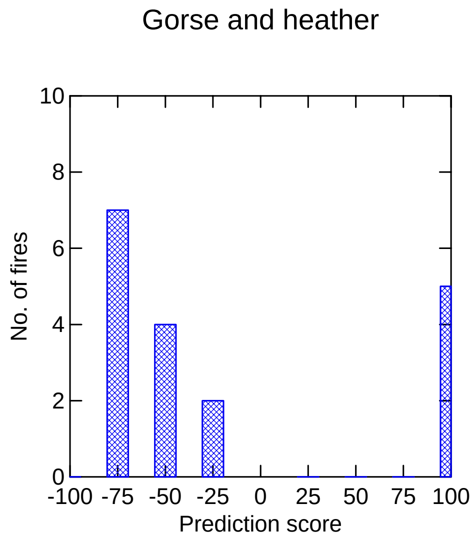


Figure 5.4 Comparison of predicted rates of spread from shrubland fire behaviour models with observed rates of spread of mallee-heath fires. Experimental fires are indicated by crosses (x) and validation fires by circles (o).

Figure 5.4 (continued below)







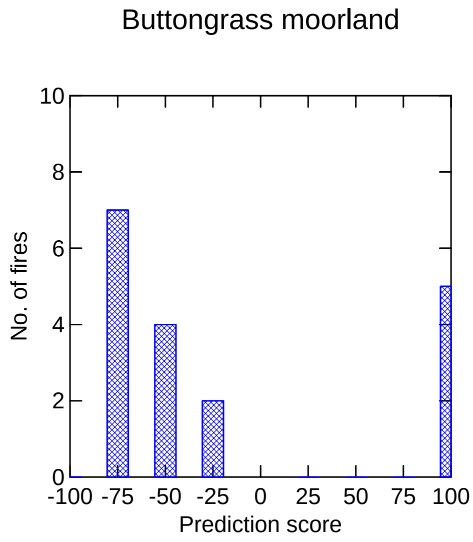


Figure 5. 5 Under- and over-prediction scores for rate of spread predictions from the gorse and heather model and the buttongrass moorland model. A prediction score of 100 indicates that the fire did not spread.

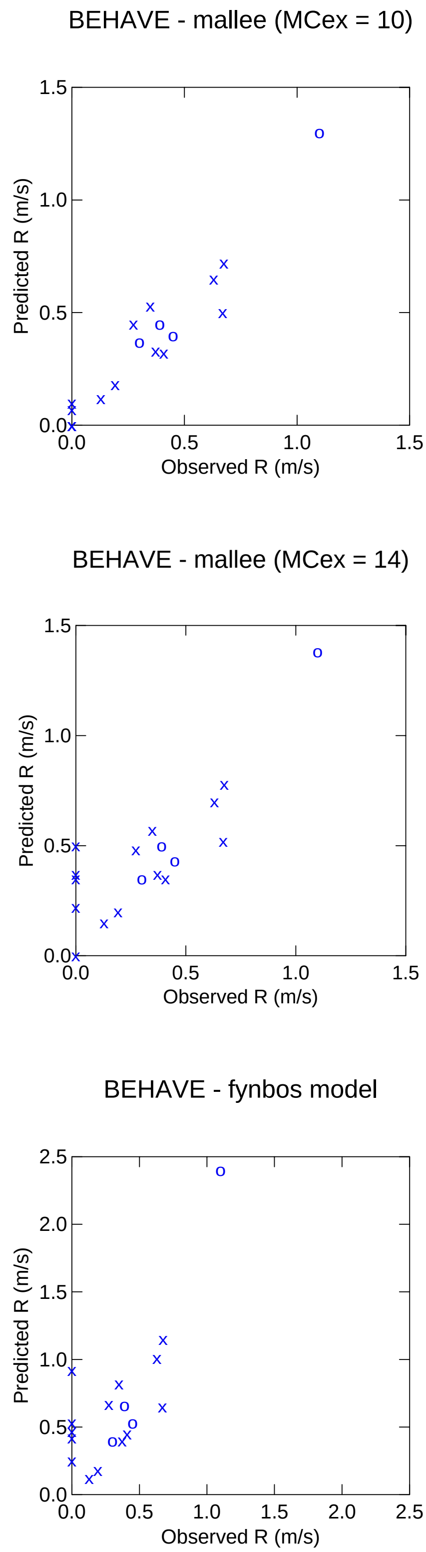


Figure 5.6 Comparison of observed rates of spread of mallee-heath fires with rates of spread predicted by BEHAVE for stylised fuel models developed for mallee-heath (refer to Table 5.1) and fynbos shrubland (Van Wilgen 1984). Predictions for the mallee-heath fuel model are shown for extinction moisture contents (MC_{ex}) of 14 per cent and 10 per cent. Experimental fires are indicated by crosses (x) and validation fires by circles (o).

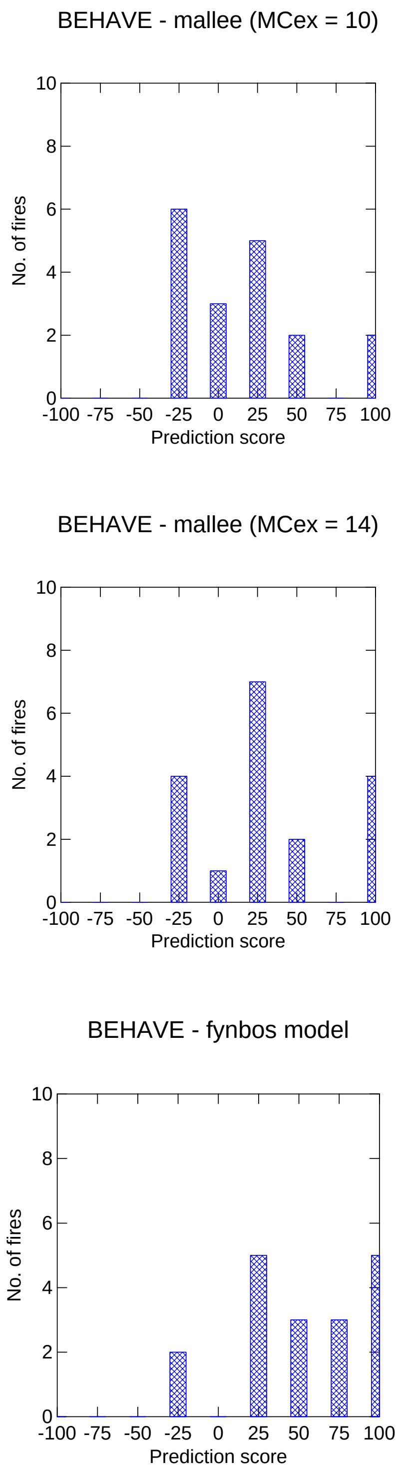


Figure 5. 7 Under- and over-prediction scores for rate of spread predictions from BEHAVE for stylised fuel models developed for mallee-heath and fynbos shrubland. Predictions for mallee-heath are shown for extinctions moisture contents (MC_{ex}) of 10 per cent and 14 per cent. A prediction score of 100 indicates that the fire did not spread.

5.3.3 Flame dimensions

Byram's model provided good predictions for flames up to 5 m long, corresponding to fire intensities of up to 8000 kW m^{-1} (Figure 5.8). At higher fire intensities the model substantially underpredicted flame length by as much as half the observed value. The distribution of under- and over-prediction scores for Byram's model was relatively symetrical (Figure 5.9). Byram (1959) proposed that in crown fire situations, flame lengths should be increased by an amount equal to half the height of the vegetation canopy to allow for flame extension. In the case of mallee-heath this correction was taken as 2 m, based on the average top height of 4 m for the taller shrubs and mallee eucalypts. Increasing the predicted flame lengths for the two most intense fires (Plots D and G) by a constant amount of 2 m improved the overall agreement between predicted and observed values (Figure 5.8). Photographs taken of both fires (Plates 2 & 14) show flames engulfing the entire vegetation profile, including the crowns of shrubs and mallees.

Flame lengths predicted by the models of Burrows and Thomas were substantially greater than those observed for mallee-heath fires, other than for the lowest intensity fire (Figure 5.8). Predictions from all three flame length models were highly correlated ($r > 0.90$, $P < 0.01$) with flame lengths observed during experimental fires.

The buttongrass moorland flame height model gave predictions of the right order across the range of the experimental data but tended to overpredict flame heights in mallee-heath, as indicated by the negatively skewed distribution of prediction scores (Figures 5.9 and 5.10). Predictions from the buttongrass model were very highly correlated ($r = 0.92$, $P = 0.002$) with observed flame heights in mallee-heath.

The model proposed by Nelson and Adkins (1986) exhibited a wide scatter and tended to overpredict flame heights in mallee-heath (Figure 5.10). The correlation between predicted and observed flame height was poorer than for any of the other models for flame dimensions ($r = 0.79$, $P = 0.04$). Use of U_2 as an approximation for mid-flame wind speed may have contributed to this variability, particularly for more intense fires with flame heights exceeded 4 m.

Flame heights predicted by the McArthur FFDM were consistently three to four times greater than those observed in mallee-heath, except for the lowest intensity fire which had flames about 1 m high.

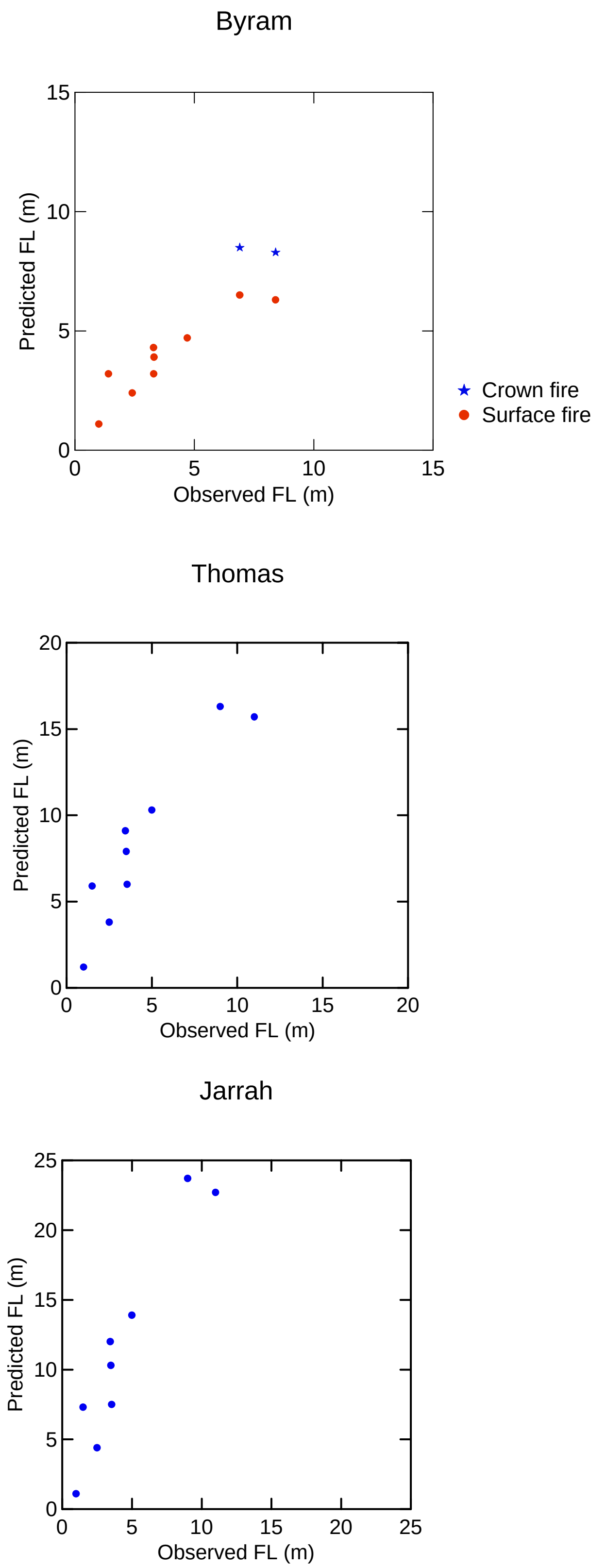
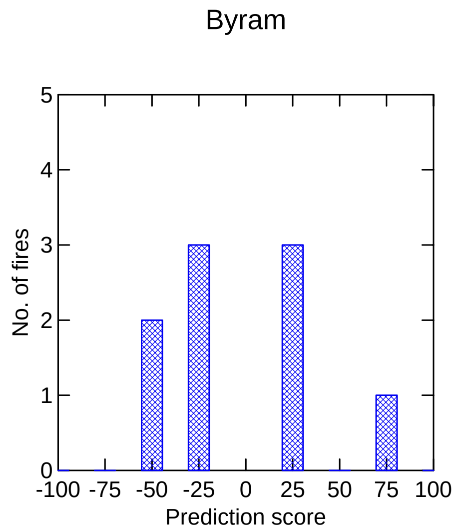


Figure 5. 8 Predicted versus observed flame lengths determined using Byram's formula, Thomas' formula and the jarrah forest fire behaviour model of Burrows (1994). Points identified as 'crown fire' on the scatterplot for Byram's formula have been adjusted by 2 metres to allow for flame extension by the canopy. Note the different scales on the vertical axis for each graph.



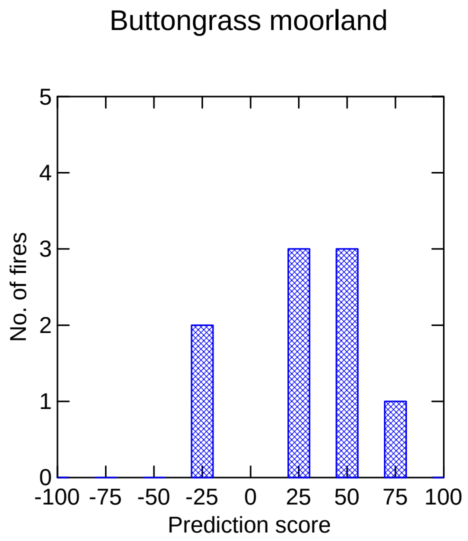


Figure 5. 9 Under- and over-prediction scores for predictions of flame length from Byram's model and flame height from Marsden-Smedley and Catchpole's buttongrass moorland model.

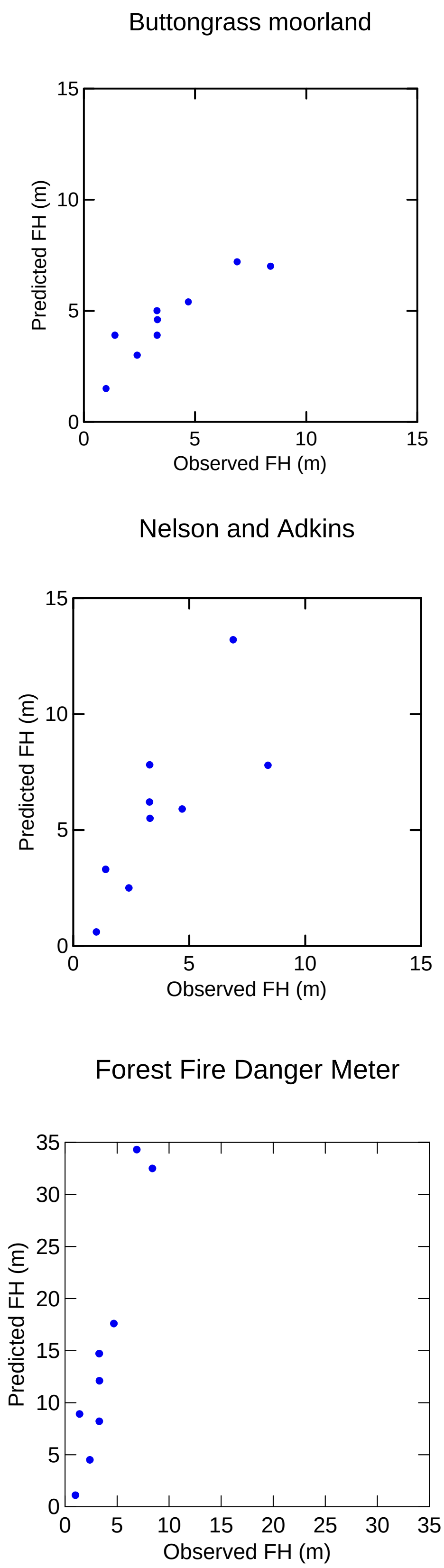


Figure 5. 10 Predicted versus observed flame heights determined using the buttongrass moorland model of Marsden-Smedley and Catchpole, the model of Nelson and Adkins, and the McArthur FFDM.

5.4 Discussion

Most of the fire danger rating systems and fire spread models examined did not clearly discriminate the conditions under which a fire would or would not sustain in mallee-heath. Exceptions to this generalisation were the ISI determined using a FFMC based on measured dead fuel moisture content, the oak chaparral spread model of Lindenmuth and Davis (1973), and the customised mallee-heath fuel model used in BEHAVE with an extinction moisture content of 10 per cent. The superior ability of the latter model to predict whether or not a fire would sustain is to be expected given that the moisture content of extinction can be specified according to observed fire behaviour. In the case of the ISI and the oak chaparral models, the experimental fires that failed to sustain tended to be associated with low index values and low predicted rates of spread, respectively. However, neither model satisfactorily discriminated all the fires that sustained from those that did not. This finding reinforces the conclusion drawn from the previous chapter that prediction of fire spread in mallee-heath requires two distinct steps: the first step being to determine whether dead fuels have reached the threshold level of dryness required for fires to sustain; the second step being to predict the forward rate of spread. Fire spread models developed for continuous fuels have tended to perform inconsistently when applied to discontinuous fuel types. For example, Griffin and Friedel (1984) reported that no consistent relationship could be established between predictions from the McArthur Mark V Grassland Fire Danger Meter and the observed behaviour of fires in mulga (*Acacia aneura*) woodlands and shrublands in arid Central Australia. They attributed this to the discontinuous nature of the fuels in mulga communities, but noted that continuous grass swards could arise in the arid zone following abnormally heavy rainfall.

Spread predictions from models that used dead fuel moisture content as an input exhibited similar trends regardless of whether M_{ls} or M_{ld} was used; predictions based on M_{ld} were however consistently lower because of the moisture damping functions include in a number of the fire behaviour models. JFDI and ISI values based on measured dead fuel moisture content were substantially higher than those based on moisture contents calculated from antecedent weather conditions. Under most circumstances, measured moisture contents would be expected to be superior to calculated moisture contents because errors associated with the use of a predictive model are avoided. This is not always the case, however: for example, Cheney *et al.* (1993) were unable to establish a statistically significant correlation between the rate of spread of grass fires and measured dead grass moisture content, but were able to correlate rate of spread with dead fuel moisture content predicted by the equations of

Noble *et al*. (1980). They attributed this to problems encountered in collecting and drying samples for moisture content determination, to the narrow range of dead fuel moisture content encountered during the experiments, and to the masking effect of other variables. The substantial difference between JFDI and ISI values calculated using the two different methods reflects the fact that the fuel moisture prediction models employed by these fire danger rating systems do not provide accurate predictions for dead fuels in mallee-heath (see Chapter 3). This is not surprising as both the jarrah SMC and the Canadian FFMC purport to represent litter beds beneath a forest canopy, rather than in an open shrubland. Solar radiation and wind are likely to have a much greater influence on fuel moisture content in mallee-heath than is taken into account by either model.

The BEHAVE system, used in conjunction with a customised fuel model for mallee-heath, provided good rate of spread predictions for the fires that sustained. Rate of spread predictions for the customised mallee-heath fuel model were much superior to those obtained in an earlier analysis (McCaw 1995) which utilised the nomograms for Fuel Model 6 (dormant brush and hardwood slash) provided by Rothermel (1983). In this earlier study, fuel Model 6 was selected because the photographs provided by Anderson (1982) were similar in appearance to mallee-heath, and because the fuel loading for the model was comparable to that measured in mallee-heath. Experimental studies aimed at validating the Rothermel fire spread model in shrubland fuel types have given variable results. Van Wilgen *et al*. (1985) reported good agreement between predictions from the Rothermel model and observed rates of spread in South African fynbos shrubland although some adjustment of the fuel depth in the stylised fuel model was necessary to achieve the optimum fit. For equivalent conditions of fuel moisture content and wind speed, rates of spread in fynbos appear to be considerably greater than those in mallee-heath. There was little difference in fine fuel loading between the stylised fuel models developed for mallee-heath and fynbos (1.15 and 1.12 kg m^{-2} respectively), but the 1 hour dead fuels in fynbos were twice as fine as those in mallee-heath (Table 5.1). The considerably higher moisture content of extinction for the fynbos model would also contribute to the faster predicted rates of spread. Catchpole (1987a, b) reported reasonable agreement between predictions from the Rothermel model and observed rates of spread in heathlands in south-eastern New South Wales. The model performed less satisfactorily in buttongrass moorlands and tended to underpredict rates of spread by about 50 per cent on average (Marsden-Smedley and Catchpole 1995b). It also predicted that the live fuel would not burn, which was incorrect.

Predictions from the buttongrass moorland model were also strongly correlated with observed rates of spread, although rates of spread in buttongrass were only about half those in mallee-heath. One obvious source of error in using the buttongrass model to predict rates of spread in mallee-heath is the different moisture damping effects in the two fuel types, with dead fuel moisture having a considerably greater affect on rate of spread in mallee-heath than in buttongrass.

Byram's flame length model and the buttongrass flame height model fitted the experimental data better than did the other models examined, all of which tended to overestimate flame dimensions in mallee-heath. The relationship between flame length and rate of spread in mallee-heath has been shown to be linear for fires with spread rates up to about 0.7 m s^{-1} (Section 4.5.10). Consequently, the relationship between flame length and fire intensity in mallee-heath will, to a first approximation, be linear because rate of spread accounts for about 85 per cent of the variation in fire intensity. This differs from the models detailed in Table 5.2 which relate fire intensity to flame length or flame height using equations of exponential form.

Under severe burning conditions, flame length and height are accentuated by combustion of elevated fuel in the shrub canopy. In addition to being elevated up to 4 m above ground level, live foliage also contains volatile oils which burn fiercely after sufficient pre-heating (Pompe and Vines 1966, Philpot 1969). For the purpose of this study flame length was defined from ground level to the tip of the flames, thereby including the section of the flaming zone which occurred within the vegetation. This definition of flame length was considered to give a more realistic indication of suppression difficulty than would the length of flames extending above the top of the canopy (ie. the fuel bed). Some authors (for example Andrews 1986) have chosen to define flame length from the top of the fuel bed. Indeed, Byram (1959) remarked that his equation would under-estimate flame length during high intensity crown fires where much of the fuel is a considerable distance above the ground, and recommended an arbitrary correction by adding one half of the canopy height to flame length. The fit of Byram's equation to the experimental data was substantially improved adding a correction of 2 m to the flame lengths for two most intense fires (Figure 5. 4), which were clearly consuming the entire vegetation profile, including the canopy layer of mallee and tall shrubs. This adjustment reduced the difference between observed and predicted flame lengths to only 0.5 m (6 per cent) for Plot G, but the difference was still substantial for for Plot D at 3.3 m (30 per cent). To make this adjustment useable in the context of fire behaviour prediction it would be necessary to identify a critical level of fire intensity above which the flames are likely to consume the canopy layer.

Based on the fit of predicted flame lengths to the experimental data (Figure 5.8) it would appear that flames predicted to more than 5 m long should be adjusted to account for consumption of crown fuel. Flames of this length would be required to ignite the crowns of shrubs and mallees, taking into consideration the fact that flame angles of 60-75° are typical for fires of this intensity. In mature mallee-heath, the forward rate of spread and frontal fire intensity corresponding to a flame length of 5 m are about 0.4 m s^{-1} and 8500 kW m^{-1} respectively.

Models for predicting flame dimensions have been found to vary in their applicability to different fuel types. Byram's formula has been found to predict flame lengths adequately for low intensity fires in heathland (Catchpole 1987a, b), and for flames up to 7 m long in fynbos shrubland (Van Wilgen *et al*. 1985). In contrast, Nelson and Adkins (1986) reported that Byram's model overpredicted flame lengths for fires of up to 2700 kW m^{-1} in a southern rough fuel type, as did Weise and Biging (1996) for laboratory fires in excelsior and stick fuels. Byram's model was found to underpredict flame length in jarrah forest (Burrows 1994) and in buttongrass moorland (Marsden-Smedley and Catchpole 1995b); in the latter case, Thomas's formula gave better overall predictions, except for two high intensity wildfires. This lack of consistency is not surprising given the great variation in the relationships between fuel bed characteristics, fire intensity and other aspects of fire behaviour (Cheney 1990). Under mild burning conditions, functional relationships developed for shallow and homogeneous fuel beds may predict flame dimensions adequately in multi-strata fuel beds, provided that only the surface fuel layer is involved in combustion. However, these simple functions become inappropriate as fire intensity increases and more of the elevated fuel is consumed. Flame dimensions may, in fact, tend to increase in a step wise fashion as each higher stratum of fuel is consumed. Fuel groupings based on vegetation structural characteristics are therefore likely to provide the most practical starting point for the development of models to predict flame dimensions and other fire behaviour characteristics (Cheney 1990).

5.5 Conclusions

Under equivalent burning conditions, rates of spread in mallee-heath were at least twice, and in some cases more than seven times as fast as predicted for most of the other shrubland fuel types. Fynbos shrubland was the only fuel type for which predicted rates of spread were consistently greater than those observed in mallee-heath;

under extreme burning conditions rates of spread in grassland and euclaypt forest were also predicted to be greater than in mallee-heath.

Existing fire danger rating systems developed for grassland and dry forest are not adequate for predicting potential fire behaviour and difficulty of suppression in mallee-heath. The principal reason for this is that they do not account for the existence of a threshold level of fuel dryness necessary for fires to sustain and spread in mallee-heath. This finding is consistent with the conclusion drawn from the previous chapter that prediction of fire spread in mallee-heath requires a two step process. The inability to predict whether conditions were suitable for fire spread in mallee heath was also identified as a shortcoming in applying number of fire spread models developed for other types of shrubland.

The Rothermel fire spread model gave good predictions of rate of spread when used in conjunction with a customised fuel model developed for mallee-heath by means of the BEHAVE system. Predictions based on a moisture content of extinction of 10 per cent were superior to those based on a moisture content of extinction of 14 per cent. Predicted rates of spread in buttongrass moorland, gorse and heather and oak chaparral were strongly correlated with, but consistently slower than rates of spread in mallee-heath.

Data from experimental fires indicates that to a first approximation, the relationship between fire intensity and flame length in mallee-heath is linear for fires up to an intensity of about 14 000 kW m^{-1}. For this reason, existing functions that relate flame length or flame height using an exponential relationship did not fit the experimental data particularly well. The fit of Byram's model for flame length was improved substantially by making an arbitrary correction that accounted for flame extension due to combustion of the canopy layer. Indeed, Byram recognised the need to adjust flame length predictions in the event of crown fires, which the more intense fires in mallee-heath represent. The flame height model developed for buttongrass moorland also gave reasonable agreement with the data for mallee-heath. Empirical models to predict flame dimensions from fire intensity are most likely to be broadly applicable if fuel groupings based on vegetation structural characteristics are employed.

CHAPTER 6

GENERAL CONCLUSIONS

The investigations described in this thesis provide the framework for a system to predict the forward rate of spread, fireline intensity and flame length of fires burning in mature mallee-heath fuels. This represents an important advancement in fire behaviour prediction for shrubland vegetation. Results from these investigations have direct application to fire management decisions about levels of preparedness, safety of firefighters and the general public, application of prescribed fire, and wildfire suppression. Until now, decisions relating to fire behaviour in mallee-heath have had to be based solely on individual experience, or on assumed similarities between mallee-heath and other fuel types.

Experiments were conducted in 20-year-old mallee-heath at the Stirling Range National Park. Shrubs <1 m tall made the greatest contribution to fuel loading and cover, and more than 80 species of vascular plants were recorded in this stratum. Mallee eucalypts and shrubs >1 m tall were also a distinctive feature of the plant community, and had an important influence on fuel characteristics because the layer of leaf litter tended to be more heavier and continuous beneath tall shrubs and mallees. Results from the experimental burning program showed that the litter layer played a crucial role in sustaining the spread of fire. Fires sustained when the moisture content of the shallow layer of litter beneath the low shrubs was 8 per cent or less. When fuels were drier than this critical threshold, flame fronts spread through the shallow litter and remained continuous. As the moisture content of the shallow litter increased, flame fronts tended to become fragmented and fires ceased to spread with a continuous front, only sustaining beneath the taller shrubs and mallees where the accumulation of litter was greater

The threshold moisture content necessary for sustained fire spread is likely to be a function of the continuity of the litter layer, and will therefore be related to the age and condition of the vegetation. This hypothesis is supported by evidence from Plot C where, despite the litter moisture content being below the 8 per cent threshold, the experimental fire failed to spread into the central part of the plot. Shrub and litter fuels in the centre of Plot C were much more discontinous than those in surrounding areas of mallee-heath and adjacent plots. Because experimental fires were conducted in vegetation of uniform age it was not possible to quantify the relationship between fuel age and threshold moisture content. This would be a worthwhile topic to investigate in any future fire behaviour studies in mallee-heath. Until this is done, fire practitioners will have to rely on their own observations to determine the threshold moisture contents for sustained fire spread in different types and ages of vegetation. The availability of portable instruments capable of accurate moisture content determination in the field, such as the Wiltronics meter (Chatto and Tolhurst 1997) and the Neosystems meter (Neosystems Inc., Perth, W. A.), should assist in the task of defining threshold moisture contents.

Wind speed accounted for about 70 per cent of the variation in forward rate of spread of experimental fires, and had a greater effect on rate of spread than any of the other variables measured. Fire spread was modelled as a function of U_2 in the open, which is a convenient exposure situation for field use. A study undertaken in mallee-heath vegetation confirmed that U_2 is equivalent to about 70 per cent of U_{10} under open conditions. Where there is a need to predict fire behaviour from wind speed forecast or measured at 10 m height then this can be converted to U_2 using the relevant equations provided in Appendix C. Inclusion of deep litter moisture content, M_{ld}, in the fire spread model accounted for a further 12-15 per cent of variation in rate of spread. There was some evidence that rate of spread was affected by the cover of mallee within experimental plots, but this was not considered sufficiently important to include in the fire spread model. Drought indices and live shrub foliage moisture content had no detectable influence on rate of spread.

Fires which sustained and spread following ignition consumed about 1.15 kg m^{-2} of fine fuel, consisting of litter (40 per cent), live fuel (40 per cent) and elevated dead fuel (20 per cent). This fuel loading is an appropriate average value on which to base calculations of fireline intensity for fires with flames longer than about 1.5 m. For fires with flames less than 1.5 m long, appropriate reduction can be made by estimating the proportion of live shrubs and elevated dead fuel that are consumed. Combustion of the crowns of mallee eucalypts and tall shrubs did not greatly increase the total quantity of fuel consumed because the majority of the fuel loading was in the low shrub stratum. However, taller plants played an important role in flame extension during more intense fires (>8500 kW m^{-1}). Live fuels up to 5 mm in diameter were consumed, although the modal diameter of live fuel consumed was generally less than 3 mm. Fuel consumption was greatest in the litter and low shrub stratum and declined with increasing height above ground.

Fires in mallee-heath spread faster than predicted for a range of other shrubland fuel types, with the exception of South African fynbos. Rates of spread in mallee-heath were up to 0.67 m s^{-1} for experimental fires and up to 1.1 m s^{-1} for reliably documented wildfires. Fireline intensities corresponding to these rates of spread are approximately 14 000 kW m^{-1} and 24 000 kW m^{-1} respectively. Average flame lengths of 9-11 m were recorded for the most intense experimental fires. The Rothermel fire model provided good rate of spread predictions when used in conjunction with a stylised fuel model for mallee-heath developed using the BEHAVE fire behaviour prediction system. The relationship between flame length and rate of spread determined from experimental data was generally linear up to a rate of spread of at least 0.67 m s^{-1}, and for this reason existing models describing flame height and length as a curvilinear function of fire intensity did not fit the experimental data particularly well. For operational use, flame lengths in mallee-heath can be determined directly from the predicted rate of spread using the regression equation developed from the experimental data. Alternatively, Byram's model provides reasonable estimates of flame length provided that a correction factor equal to half the top height of the vegetation is added to the predicted flame length in situations where the crowns of tall shrubs and mallees are consumed by fire. This will generally occur once the fireline intensity exceeds 8500 kW m^{-1}.

Fire managers often wish to predict in advance whether a fire is likely to spread, and what the resulting rate of spread will be. To make such predictions for mallee-heath it is important to know the moisture content of both the shallow and deep litter layers. The diurnal EMC model developed by Nelson (1991) was found to have considerable promise for predicting fuel moisture content in mallee-heath, and gave more accurate predictions than several commonly-used empirical models. An important advantage of this model is that it can predict the moisture content of different dead fuel components, provided that appropriate inputs for response time and fuel level temperature and relative humidity are used. The reponse time of shallow litter was found to be about 1 hour, and measured moisture contents for litter samples and litter baskets matched well with predictions based on ground level conditions exposed to full sunlight. The model also provided good predictions for litter in partial shade at Perup, the response time also being 1 to 2 hours. Elevated dead leaves of *D. drummondii* had a longer response time than did litter fuels, with a response time of 2 to 3 hours resulting in the best fit of the model to field data. Variation in the response time of *D. drummondii* between experiments conducted at Perup and the Stirling Range may relate to the degree of weathering of the leaves used to prepare the samples. Experimental results demonstrated that moisture content predictions derived from screen level weather observations were only slightly less accurate than predictions derived from measured fuel temperatures. The empirical relationships of Byram and Jemison (1943) and Nelson (1991) were found to be adequate for predicting fuel level temperature and relative humidity respectively from screen level conditions. Amelioration of solar radiation by the vegetation canopy would need to be taken into account in calculating the temperature of litter fuels in partial shade. Fuel level temperature and humidity could also be predicted using the physically based surface energy balance model validated by Viney (1992), but this more complex model was not evaluated as part of the investigations decribed here.

Preliminary observations suggest that dead fuels in mallee-heath dry much more rapidly after rain than is the case for litter fuels in open eucalypt forest. For this reason, fire danger rating and fire behaviour prediction systems developed for eucalypt forests will tend to under-estimate fire behaviour in mallee-heath if the predictions are based on dead fuel moisture contents calculated from antecedent weather conditions. Current experience indicates that prior rainfall is unlikely to influence the moisture content of shallow litter and elevated dead fuel after more than one dry day has elapsed. Deep litter may reflect rainfall effects for a longer period, perhaps up to five days, but further work is need to quantify this.

Live shrubs comprise approximately 40 per cent of the fine fuel load in mallee-heath, and therefore have an important influence on fire behaviour. Foliar moisture contents for two shrubs (*D. drummondii*, *L. inermis*) and a mallee eucalypt (*E. pachyloma*) were measured at monthly intervals over one year, and additional observations were available for *D. drummondii* over a period of several years. The moisture content of mature live foliage remained between 70 and 100 per cent throughout the year for each species, and there was little variation from month to month for *D. drummondii* or *L. inermis*. Based on these results, an average moisture content of 85 per cent was used as the input to fire behaviour models which require an estimate of live fuel moisture content. There was some evidence that the moisture content of *E. pachyloma* foliage is more responsive than the foliage of the other species to environmental conditions; further sampling is required to confirm this. Foliage moisture contents were not correlated with the SDI or KBDI over the period for which measurements were available, but additional sampling over at least another annual cycle is desirable before firm conclusions are reached about their relationship to seasonal drought conditions.

Validation against spread observations from a limited number of prescribed and wild fires indicates that the mallee-heath fire spread model developed from experimental data provides robust predictions over a broad range of burning conditions. Every opportunity should be taken to gather additional fire spread observations from wildfires so that the predictive capability of the model can be further tested for fires burning under severe weather conditions.

REFERENCES

Albini, F. A. 1976. Estimating wildfire behaviour and effects. United States Department of Agriculture, Forest Service, General Technical Report INT-30, Intermountain Research Station, Ogden, Utah. 92 pages.

Albini, F. A. 1981. A model for the wind-blown flame from a line fire. Combustion and Flame 43: 155-174.

Albini, F. A. 1985. A model for fire spread in wildland fuels by radiation. Combustion Science and Technology 42: 229-258.

Albini, F. A. 1986. Wildland fire spread by radiation - a model including fuel cooling by natural convection. Combustion Science and Technology 45: 101-113.

Albini, F. A. and R. G. Baughmann. 1979. Estimating windspeeds for predicting wildland fire behaviour. United States Department of Agriculture, Forest Service, Research Paper INT-221, Intermountain Research Station, Ogden, Utah.10 pages.

Albini, F. A. and B. J. Stocks. 1986. Predicted and observed rates of spread of crown fires in immature jack pine. Combustion Science and Technology 48: 65-76.

Alexander, M. E. 1982. Calculating and interpreting forest fire intensities. Canadian Journal of Botany 60: 349-357.

Alexander, M. E. and W. J. De Groot. 1988. Fire behaviour in Jack Pine stands as related to the Canadian Forest Fire Weather Index (FWI) System. Canadian Forestry Service, Northern Forestry Centre, Edmonton, Alberta.

Alexander, M. E. and R. A. Lanoville. 1989. Predicting fire behaviour in the Black Spruce-Lichen Woodland fuel type. Forestry Canada, Northern Forestry Centre, Edmonton, Alberta.

Alexander, M. E. and D. Quintilio. 1990. Perspectives on experimental fires in Canadian forestry research. Mathematical and Computer Modelling 13 (12):17-26.

Anderson, H. E. 1969. Heat transfer and fire spread. United States Department of Agriculture, Forest Service, Research Paper INT-69, Intermountain Research Station, Ogden, Utah. 20 pages.

Anderson, H. E. 1982. Aids to determining fuel models for estimating fire behaviour. United States Department of Agriculture, Forest Service, General Technical Report INT-122, Intermountain Research Station, Ogden, Utah. 22 pages.

Anderson, H. E. 1990a. Moisture diffusivity and response time in fine forest fuels. Canadian Journal of Forest Research 20: 315-325.

Anderson, H. E. 1990b. Predicting equilibrium moisture content of some foliar forest litter in the Northern Rocky Mountains. United States Department of Agriculture, Forest Service, Research Paper INT-429, Intermountain Research Station, Ogden, Utah. 10 pages.

Anderson, H. E. and Rothermel, R. C. 1965. Influence of moisture and wind upon the characteristics of free-burning fires. In: Tenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Pennsylvania, pages 1009-1019.

Anderson, H. E., R. D. Schuette, and R. W. Mutch. 1978. Timelag and equilibrium moisture content of ponderosa pine needles. United States Department of Agriculture, Forest Service, Research Paper INT-202, Intermountain Research Station, Ogden, Utah. 10 pages.

Andrews, P. L. 1980. Testing the fire behavior model. Proceedings of the Sixth Conference on Fire and Forest Meteorlogy, 22-24 April, Seattle, Washington. Society of American Foresters, Washington D. C., pages 70-77.

Andrews, P. L. 1986. BEHAVE: Fire behaviour and fuel modeling system. BURN Subsystem, Part 1. United States Department of Agriculture, Forest Service, General Technical Report INT-194, Intermountain Research Station, Ogden, Utah. 130 pages.

Andrews, H. P., R. D. Snee, and M. H. Sarner. 1980. Graphical display of means. The American Statistician 34: 195-199.

Anonymous. 1975. Manual of meteorology. Part 1 - General Meteorology. Department of Science and Technology, Bureau of Meteorology. Australian Government Publishing Service, Canberra. 149 pages.

Anonymous. 1984. Tables for the Canadian Forest Fire Weather Index System, (4th edition). Canadian Forestry Service Forestry Technical Report 25, Environment Canada.

Anonymous. 1991. Monthly weather review for Western Australia - 1991. Commonwealth of Australia, Bureau of Meteorology. Perth, Western Australia.

Arya, S. P. 1988. Introduction to micrometeorology. Academic Press, San Diego. 303 pages.

Bannister, A. J. and B. N. Hanstrum. 1995. A climatology of very high and extreme fire weather days in southern Western Australia. Poster abstract. CALMScience Supplement 4: 210.

Beard, J. S. 1984. Biogeography of the kwongan. In: Kwongan - plant life of the sandplain. (edited by J. S. Pate and J. S. Beard), University of Western Australia Press, Nedlands, Western Australia, pages 1-26.

Beard, J. S. and J. S. Pate. 1984. Foreword: Kwongan - plant life of the sandplain. In: Kwongan - plant life of the sandplain (edited by J. S. Pate and J. S. Beard), University of Western Australia Press, Nedlands, Western Australia, pages xvii-xxii.

Beer, T. 1990. Applied Environmetrics meteorological tables. Applied Environmetrics, 118 Gordon Street, Balwyn, Victoria, Australia.

Beggs, B. J. 1976. Forest fire behaviour tables for Western Australia. Western Australian Department of Conservation and Land Management, Perth.

Benson, D. H. 1985. Maturation periods for fire sensitive shrub species in Hawkesbury sandstone vegetation. Cunninghamia 1: 339-349.

Bevins, C. D. 1976. Fire modeling for natural fuel situations in Glacier National Park. In: First conference on scientific research in the National Parks, New Orleans.

Billing, P. 1981. Hazard reduction burning in the Big Desert. Victorian Department of Conservation and Environment, Fire Management Branch, Research Report No. 9. 4 pages.

Birk, E. M. and R. W. Simpson. 1980. Steady state and the continuous input model of litter accumulation and decomposition in Australian eucalypt forests. Ecology 61: 481-485.

Blackmarr, W. H. and W. R. Flanner. 1968. Seasonal and diurnal variation in moisture content of six species of pocosin shrubs. United States Department of Agriculture, Forest Service, Research Paper SE-33, Southeastern Forest and Range Experiment Station, Asheville, North Carolina. 11 pages.

Blank, R. W. and A. J. Simard. 1983. An electronic timer for measuring spread rates of wildland fires. United States Department of Agriculture, Forest Service, Research Note NC-304, North Central Experiment Station, St Paul, Minnesota. 4 pages.

Bradstock, R. A. 1989. Dynamics of a perennial understorey. In: Mediterranean landscapes in Australia - Mallee ecosystems and their management (edited by J. C. Noble and R. A. Bradstock). Commonwealth Scientific and Industrial Research Organisation, East Melbourne, Australia, pages 141-154.

Bradstock, R. A. and P. J. Myerscough. 1988. The survival and population response to frequent fires of two woody resprouters *Banksia serrata* and *Isopogon anemonifolius*. Australian Journal of Botany 36: 415-431.

Bradstock, R. A. and A. M. Gill. 1993. Fire in semi-arid, mallee shrublands: size of flames from discrete fuel arrays and their role in the spread of fire. International Journal of Wildland Fire 3: 3-12.

Bradstock, R. A., M. Bedward, J. Scott and D. A. Keith. 1996. Simulation of the effect of spatial and temporal variation in fire regimes on the population viability of a *Banksia* species. Conservation Biology 10: 776-784.

Bransbury, D. I. and N. M. Tainton. 1977. The disc pasture meter: possible applications in grazing management. Proceedings of the Grassland Society of South Africa 5: 115-118.

Brown, J. K. 1970. Ratios of surface area to volume for common fine fuels. Forest Science 16: 101-105.

Brown, A. A. and K. P. Davis. 1973. Forest fire: Control and Use. 2nd edition. McGraw-Hill, New York.

Brown, J. K., G. D. Booth, and D. G. Simmerman. 1989. Seasonal changes in live fuel moisture content in Western U.S. Aspen. In: Proceedings of the Tenth Conference on Fire and Forest Meteorology, Ottawa, April 17-21, pages 406-412.

Brown, J. M. and A. J. M. Hopkins. 1983. The kwongan (sclerophyllous shrublands) of Tutanning Nature Reserve, Western Australia. Australian Journal of Ecology 8: 63-73.

Bruner, A. D and D. A. Klebenow. 1979. Predicting success of prescribed fires in Pinyon-Juniper woodland in Nevada. United States Department of Agriculture, Forest Service, Research Paper INT-219, Intermountain Research Station, Ogden, Utah. 11 pages.

Burgan, R. E. and R. C. Rothermel. 1984. BEHAVE. Fire behavior prediction and fuel modeling system - fuel subsystem. United States Department of Agriculture, Forest Service, General Technical Report INT-167, Intermountain Research Station, Ogden, Utah. 126 pages.

Burrows, N. D. 1984. Describing forest fires in Western Australia - a guide for fire managers. Forests Department of Western Australia, Technical Paper No. 9. 29 pages.

Burrows, N. D. 1987. The Soil Dryness Index for use in fire control in the south-west of Western Australia. Western Australian Department of Conservation and Land Management, Technical Report No. 17. 37 pages.

Burrows, N. D. 1994. Experimental development of a fire management model for jarrah (*Eucalyptus marginata* Donn ex Sm) forest. Unpublished Doctoral Thesis, Department of Forestry, Australian National University, Canberra. 291 pages.

Burrows, N., L. McCaw, and G. Friend 1987. Fire management on nature conservation lands. Western Australian Department of Conservation and Land Management Occasional Paper 1/89. 186 pages.

Burrows, N. D. and W. L. McCaw. 1989. Fuel characteristics and bushfire control in Banksia low woodlands in Western Australia. Journal of Environmental Management 31(3): 229-236.

Burrows, N. D., B. Ward and A. Robinson. 1990. Fire behaviour in spinifex fuels on the Gibson Desert Nature Reserve, Western Australia. Journal of Arid Environments 20, 189-204.

Byram, G. M. 1959. Combustion of forest fuels. In: Forest fire: Control and Use (edited by K. P. Davis), McGraw-Hill, New York, pages 61-89.

Byram, G. M. 1963. An analysis of the drying process in forest fuel material. Paper presented at the 1963 International Symposium on Humidity and Moisture, May 20-23 1963, Washington DC.

Byram, G. M and G. M. Jemison. 1943. Solar radiation and forest fuel moisture. Journal of Agricultural Research 67: 149-176.

Campbell, D., T. Raley and R. Megli. 1994. Rethinking how fuels are heated and dried. Wildfire 3: 27-28.

Catchpole, W. 1985. Predicting biomass for *Casuarina nana* for input into the Rothermel fire model. Report No. 24/85, Department of Mathematics, Faculty of Military Studies, University of New South Wales, Duntroon, Australian Capital Territory.

Catchpole, W. 1987a. Fire models for heathland. Part 1. *Casuarina nana*. Report No. 5/87, Department of Mathematics, Australian Defence Force Academy, University of New South Wales, Campbell, Australian Capital Territory.

Catchpole, W. 1987b. Fire models for heathland. Part 2. Coastal heathland. Report No. 6/87, Department of Mathematics, Australian Defence Force Academy, University of New South Wales, Campbell, Australian Capital Territory.

Catchpole, W. C. and C. J. Wheeler. 1992. Estimating plant biomass: A review of techniques. Australian Journal of Ecology 17: 121-131.

Catchpole, W. R. and E. A. Catchpole. 1993. Stratified double sampling of patchy vegetation to estimate biomass. Biometrics 49: 295-303.

Catchpole, W., R. Bradstock, J. Choate, L. Fogarty, N. Gellie, G. McArthy, L. McCaw, J. Marsden-Smedley and G. Pearce. 1998. Cooperative development of equations for heathland fire behaviour. Paper to the Third International Conference on Forest Fire Research/ 14th Conference on Fire and Forest Meteorology, 16-20 November 1998, Luso-Coimbra, Portugal.

Catchpole, W. R., E. A. Catchpole, N. R. Viney, W. L. McCaw and J. B. Marsden-Smedley. In press. Modelling fuel response time and equilibrium moisture content from field data. International Journal of Wildland Fire (accepted for publication November 1997).

Chandler, C., N. P. Cheney, P. Thomas, L. Trabaud, and D. Williams. 1983. Fire in forestry - Volume 1. John Wiley and Sons, New York. 450 pages.

Chapman, A. and K. R. Newbey. 1994. Revegetation and recolonisation by vertebrates of Fitzgerald River National Park, Western Australia following 1985 wildfire. Western Australian Department of Conservation and Land Management, Landnote 1/94.

Chatto, K. and K. Tolhurst. 1997. Development and testing of the Wiltronics T-H moisture meter. Victorian Department of Natural Resources and Environment, Fire Management Branch, Research Report 46. Victoria, Australia. 40 pages.

Cheney, N. P. 1981. Fire behaviour. In: Fire and the Australian biota (edited by A. M. Gill, R. H. Groves, and I. R. Noble), Australian Academy of Sciences, Canberra, pages 151-176.

Cheney, N. P. 1990. Quantifying bushfires. Mathematical and Computer Modeling 13: 9-15.

Cheney, N. P. 1991. Models used for fire danger rating in Australia. In: Proceedings of a Conference on Bushfire Modelling and Fire Danger Rating Systems (edited by N. P. Cheney and A. M. Gill), Commonwealth Scientific and Industrial Research Organisation, Canberra, pages 19-28.

Cheney, N. P., J. S. Gould, and A. A. G. Wilson. 1987. Preliminary results from the Grassland Fire Behaviour Experiments, Northern Territory, July-August 1986. Progress report, National Bushfire Research Unit, Commonwealth Scientific and Industrial Research Organisation, Canberra.

Cheney, N. P., A. A. G. Wilson, and L. McCaw 1990. Development of an Australian fire danger rating system. Unpublished report on Rural Industries Research and Development Corporation Project No. CSF-35A. 24 pages.

Cheney, N. P., J. S. Gould, and I. Knight. 1992. A prescribed burning guide for young regrowth forests of Silvertop Ash. Forestry Commission of New South Wales. 92 pages.

Cheney, N. P., J. Gould, and W. R. Catchpole. 1993. The influence of fuel, weather and fire shape variables on fire-spread in grasslands. International Journal of Wildland Fire 3(1): 31-44.

Cheney, N. P. and J. S. Gould. 1995. Fire growth in grassland fuels. International Journal of Wildland Fire 5(4): 237-247.

Cheney, N. P. and J. S. Gould. 1997. Letter: fire growth and acceleration. International Journal of Wildland Fire 7(1): 1-6.

Cheney, N. P., J. S. Gould and L. McCaw. 1996. Project Vesta: a research initiative into the effects of fuel structure and fuel load on behaviour of wildfires in dry eucalypt forest. Paper to the 13th Conference on Fire and Forest Meteorology, October 28-31, Lorne, Australia.

Chrosciewicz, Z. 1986. Foliar moisture content content variations in four coniferous tree species of central Alberta. Canadian Journal of Forest Research 16: 157-162.

Churchward, H. M., W. M. McArthur, P. L. Sewell, and G. A. Bartle. 1988. Landforms and soils of the southcoast and hinterland, Western Australia. CSIRO Division of Water Resources Divisional Report 88/1.

Condon, R. W. 1979. The modified grassland fire danger meter for arid zone rangelands. In: Proceedings of the Australian Rangelands Society Conference, Adelaide.

Conroy, B. 1993. Fuel management strategies for the Sydney region. In: The burning question: fire management in NSW (edited by J. Ross), University of New England, Armidale, New South Wales, pages 73-81.

Countryman, C. M. 1977. Radiation effects on moisture variation in ponderosa pine. United States Department of Agriculture, Forest Service, Research Paper PSW-126, Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 23 pages.

Courtney, J. 1993. Climate. In: The Stirling Range - a natural history (edited by C. Thompson, G. Hall, and G. Friend), Western Australian Department of Conservation and Land Management, Perth, pages 5-12.

Crane, W. J. B. 1982. Computing grassland and forest fire behaviour, relative humidity, and drought index by pocket calculator. Australian Forestry 45 (2): 89-97.

Crombie, D. S. 1992. Root depth, leaf area and daytime water relations of jarrah (*Eucalyptus marginata*) forest overstorey and understorey during summer drought. Australian Journal of Botany 40: 113-122.

Crombie, D. S., J. T. Tippett, and T. C. Hill. 1988. Dawn water potential and root depth of trees and understorey species in south-western Australia. Australian Journal of Botany 36: 621-631.

Crook, I. G. and A. A. Burbidge. 1982. Lake Magenta Nature Reserve. Western Australian Department of Fisheries and Wildlife Nature Reserve Management Plan No. 4. 44 pages.

Davis, J. R. and J. H. Dieterich. 1976. Predicting rate of spread (ROS) in Arizona oak chaparral: field workbook. United States Department of Agriculture, Forest Service, General Technical Report RM-24, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. 8 pages.

Deeming, J. E., J. W. Lancaster, M. A. Fosberg, R. W. Furman and M. J. Schroeder 1972. National Fire-danger rating system. United States Department of Agriculture, Forest Service, Research Paper RM-84, Rocky mountain Forest and Range Experiment Station, Fort Collins, Colorado. 165 pages.

Deeming, J. E., R. E. Burgan, and J. D. Cohen. 1977. The National Fire-danger Rating System - 1978. United States Department of Agriculture, Forest Service, General Technical Report INT-39, Intermountain Research Station, Ogden, Utah. 63 pages.

Delfs, J. C., J. S. Pate, and D. T. Bell. 1987. Northern Sandplain Kwongan: community biomass and selected species response to fire. Journal of the Royal Society of Western Australia 69(4): 133-138.

Dell, J. D. and C. W. Philpot. 1965. Variations in the moisture content of several fuel size components of live and dead chamise. United States Department of Agriculture, Forest Service, Research Note PSW-83, Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 7 pages.

Dodd, J. and D. T. Bell. 1993a. Water relations of the canopy species in a *Banksia* woodland, Swan Coastal Plain, Western Australia. Australian Journal of Ecology 18: 281-293.

Dodd, J. and D. T. Bell. 1993b. Water relations of understorey shrubs in a *Banksia* woodland, Swan Coastal Plain, Western Australia. Australian Journal of Ecology 18: 295-305.

Durre, A. M. and T. Beer. 1989. Wind information prediction study: Annaburroo meteorological data analysis. CSIRO Division of Atmospheric Research Technical Paper No. 17. 30 pages.

Duxbury, G. 1984. Winter burning program in mallee and heath country. Letter on file. Western Australian Department of Conservation and Land Management, Perth.

Frandsen, W. H. and P. L. Andrews. 1979. Fire behaviour in non-uniform fuels. United States Department of Agriculture, Forest Service, Research Paper INT-232, Intermountain Research Station, Ogden, Utah. 34 pages.

Fogarty, L. G. 1993. The accumulation and structural development of the wiregrass (*Tetrarrhena juncea*) fuel type in East Gippsland. Victorian Department of Conservation and Natural Resources, Fire Management Branch, Research Report Number 37. 29 pages.

Forestry Canada. 1992. Development and structure of the Canadian forest fire behaviour prediction system. Forestry Canada Fire Danger Group, Information Report ST-X-3.

Fox, B. J., M. D. Fox and G. M. McKay. 1979. Litter accumulation after fire in a eucalypt forest. Australian Journal of Botany 27: 157-165.

Garratt, J. R. 1980. Surface influence upon vertical profiles in the atmospheric near-surface layer. Quarterly Journal of the Royal Meteorological Society 106: 803-819.

Gary, H. L. 1971. Seasonal and diurnal changes in moisture contents and water deficits of Englemann spruce needles. The Botanical Gazette 132(4): 327-332.

George, A. S., A. J. M. Hopkins and N. G. Marchant. 1979. The heathlands of Western Australia. In: Heathlands and related shrublands of the world. A. Descriptive Studies (edited by R. L. Specht), Elsevier, Amsterdam, pages 211-230.

Gill, A. M. 1975. Fire and the Australian flora. Australian Forestry 38: 4-25.

Gill, A. M. 1981. Adaptive responses of Australian vascular plant species to fires. In: Fire and the Australian biota (edited by A. M. Gill, R. H. Groves, and I. R. Noble), Australian Academy of Sciences, Canberra, pages 243-271.

Gill, A. M., W. S. W. Trollope, and D. A. McArthur. 1978. Role of moisture in the flammability of natural fuels in the laboratory. Australian Forest Research 8: 199-208.

Gill, A. M. and A. McMahon. 1986. A post-fire chronosequence of cone, follicle and seed production in *Banksia ornata*. Australian Journal of Botany 34: 425-433.

Gill, A. M. and A. O. Nicholls. 1989. Monitoring fire-prone flora in reserves for nature conservation. In: Fire management on nature conservation lands (edited by N. Burrows, L. McCaw and G. Friend). Western Australian Department of Conservation and Land Management Occasional Paper 1/89, pages 137-152.

Gill, A. M. and I. K. Knight. 1991. Fire measurement. In: Proceedings of a Conference on Bushfire Modelling and Fire Danger Rating Systems (edited by N. P. Cheney and A. M. Gill), Commonwealth Scientific and Industrial Research Organisation, Canberra, pages 137-146.

Gill, A. M., N. D. Burrows, and R. A. Bradstock. 1995. Fire modelling and fire weather in an Australian desert. CALMScience Supplement 4: 29-34.

Gould, J. S. 1991. Validation of the Rothermel fire spread model and related fuel parameters in grassland fuels. In: Proceedings of a Conference on Bushfire Modelling and Fire Danger Rating Systems (edited by N. P. Cheney and A. M. Gill), Commonwealth Scientific and Industrial Research Organisation, Canberra, pages 51-64.

Griffin, G. F. and G. E. Allan. 1984. Fire behaviour. In: Anticipating the inevitable: a patch-burning strategy for fire management at Uluru (Ayers Rock-Mt Olga) National Park. Commonwealth Scientific and Industrial Research Organisation, Melbourne, pages 55-68.

Griffin, G. F. and M. H. Friedel. 1984. Effects of fire on central Australian rangelands. 1. Fire and fuel characteristics and changes in herbage and nutrients. Australian Journal of Ecology 9: 381-393.

Green, J. W. 1985. Census of the vascular plants of Western Australia. Western Australian Department of Agriculture, Perth.

Green, L. R. 1981. Burning by prescription in chaparral. United States Department of Agriculture, Forest Service, General Technical Report PSW-51, Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 36 pages.

Hanstrum, B. N. 1990. Fire weather in relation to tropical cyclones over southwest Western Australia. In: Proceedings of the Third Australian Fire Weather Conference, 18-20 May 1989, Hobart, Tasmania. Bureau of Meteorology, pages 79-84.

Hanstrum, B. N., K. J. Wilson, and S. L. Barrell. 1990. Pre-frontal troughs over southern Australia. Part 1: climatology. Weather and Forecasting 5(1): 22-31.

Herford, I., K. Gillen, M. Lloyd, C. Hine, L. McCaw, and G. Keighery 1996. Stirling Range and Porongurup National Parks draft management plan. Department of Conservation and Land Management, Perth, Western Australia.

Hill, K. D. 1989. Mallee eucalypt communities: Their classification and biogeography. In: Mediterranean landscapes in Australia - Mallee ecosystems and their management (edited by J. C. Noble and R. A. Bradstock). Commonwealth Scientific and Industrial Research Organisation, East Melbourne, Australia, pages 93-108.

Hobbs, R. J. 1987. Disturbance regimes in remnants of natural vegetation. In: Nature Conservation - the role of remnants of native vegetation (edited by D. A. Saunders, G. W. Arnold, A. A. Burbidge, and A. J. M. Hopkins), Surrey Beatty and Sons, Chipping Norton, New South Wales, pages 233-240.

Hobbs, R. J. and C. H. Gimmingham. 1984. Studies on fire in Scottish heathland communities. Journal of Ecology 72: 223-240.

Hobbs, R. J. and L. Atkins. 1988. Spatial variability of experimental fires in south-west Western Australia. Australian Journal of Ecology 13: 295-299.

Jameson, D. A. 1966. Diurnal and seasonal fluctuations in moisture content of Pinyon and Juniper. United States Department of Agriculture, Forest Service, Research Note RM-67, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. 7 pages.

Jenny, H., S. P. Gessel, and F. T. Bingham. 1949. Comparative study of decomposition rates of organic matter in temperate and tropical regions. Soil Science 68: 419-432.

Jones, P. M. 1973. Report on Stirling Range fire study. Unpublished report on file at Department of Conservation and Land Management Research Centre, Manjimup.

Jones, P. M. 1974. Stirling Range fire behaviour study - current development (November 1974). Unpublished report on file at Department of Conservation and Land Management Research Centre, Manjimup.

Kayll, A. J. 1966. Some characteristics of heath fires in N. E. Scotland. Journal of Applied Ecology 3: 29-40.

Keetch, J. J. and G. M. Byram. 1968. A drought index for forest fire control. United States Department of Agriculture, Forest Service, Research Paper SE-38, Southeastern Forest Experiment Station, Asheville, North Carolina. 32 pages.

Keighery, G. and J. Beard. 1993. Plant communities. In: The Stirling Range - a natural history (edited by C. Thompson, G. Hall, and G. Friend), Western Australian Department of Conservation and Land Management, Perth, pages 43-54.

Kessel, S. R., M. W. Potter, C. D. Bevins, L. Bradshaw, and B. W. Jeske. 1978. Analysis and application of forest fuels data. Environmental Management 2(4): 347-363.

King, N. K. 1973. The influence of water vapour on the emission spectra of flames. Combustion Science and Technology 6: 247-256.

Klavseth, T. O. 1985. Cautionary note about R^2. The American Statistician 39: 279-285.

Kruger, F. J. 1977. A preliminary account of aerial plant biomass in fynbos communities of the mediterranean-type climate zone of the Cape Province. Bothalia 12 (2): 301-307.

Kruger, F. J. and H. C. Taylor. 1979. Plant species diversity in Cape fynbos: gamma and delta diversity. Vegetatio 41: 85-93.

Lamont, B. B., A. J. M. Hopkins, and R. J. Hnatiuk. 1984. The flora - composition, diversity and origins. In: Kwongan - plant life of the sandplain (edited by J. S. Pate and J. S. Beard), University of Western Australia Press, Nedlands, Western Australia, pages 27-50.

Leopold, A. C. and P. E. Kriedemann. 1975. Plant growth and development. Tata McGraw-Hill, New York. 545 pages.

Levy, E. B. and E. A. Madden. 1933. The point method of pasture analysis. New Zealand Journal of Agriculture 46: 267-79.

Lindenmuth, A. W. and J. R. Davis. 1973. Predicting fire spread in Arizona's oak chaparral. United States Department of Agriculture, Forest Service, Research Paper RM-101, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. 11 pages.

Loomis, R. M. and R. W. Blank. 1981. Summer moisture content of some northern lower Michigan understorey plants. United States Department of Agriculture, Forest Service, Research Paper NC-263, North Central Forest Experiment Station, St Paul, Minnesota. 4 pages.

Luke, R. H. and A. G. McArthur. 1978. Bushfires in Australia. Australian Government Publishing Service, Canberra. 359 pages.

Martin, H. A. 1989. Evolution of Mallee and its environment. In: Mediterranean landscapes in Australia - Mallee ecosystems and their management (edited by J. C. Noble and R. A. Bradstock). Commonwealth Scientific and Industrial Research Organisation, East Melbourne, Australia, pages 83-92.

Marsden-Smedley, J. B. and W. R. Catchpole. 1995a. Fire behaviour modelling in Tasmanian buttongrass moorlands. 1. Fuel characteristics. International Journal of Wildland Fire 5(4): 203-214.

Marsden-Smedley, J. B. and W. R. Catchpole. 1995b. Fire behaviour modelling in Tasmanian buttongrass moorlands. 11. Fire behaviour. International Journal of Wildland Fire 5(4): 215-228.

Marsden-Smedley, J, W. Catchpole and A. Pyrke. 1998. Unbounded burning in Tasmanian buttongrass moorlands. Report prepared for the Tasmanian Fire Research Fund, Hobart, Tasmania. 34 pages.

McArthur, A. G. 1962. Control burning in eucalypt forests. Commonwealth of Australia Forestry and Timber Bureau Leaflet Number 80, Canberra, ACT. 31 pages.

McArthur, A. G. 1966. Weather and grassland fire behaviour. Department of Natural Development, Forestry and Timber Bureau, Leaflet 100. 23 pages.

McArthur, A. G. 1967. Fire behaviour in eucalypt forests. Commonwealth of Australia Forestry and Timber Bureau Leaflet Number 107. 36 pages.

McArthur, A. G. 1972. Fire control in arid and semi-arid lands of Australia. In: The use of Trees and Shrubs in the Dry Country of Australia (edited by N. Hall *et al.*), Australian Government Publishing Service, Canberra, pages 488-516.

McArthur, A. G. 1973. Grassland Fire Danger Meter Mark 4. Commonwealth of Australia Forestry and Timber Bureau.

McArthur, A. G. 1977. Grassland Fire Danger Meter Mark 5. Country Fire Authority, Victoria.

McCaw, W. L. 1991. Measurement of fuel quantity and structure for bushfire research and management. In: Proceedings of a Conference on Bushfire Modelling and Fire Danger Rating Systems (edited by N. P. Cheney and A. M. Gill), Commonwealth Scientific and Industrial Research Organisation, Canberra, pages 147-156.

McCaw, W. L. 1992. Fire management in semi-arid woodlands and shrublands in the south of Western Australia. International Forest Fire Newsletter 6:18-19.

McCaw, W. L. 1995. Predicting fire spread in Western Australian mallee-heath. CALMScience Supplement 4: 35-42.

McCaw, L., T. Maher, and K. Gillen. 1992. Wildfires in the Fitzgerald River National Park, Western Australia, December 1989. Western Australian Department of Conservation and Land Management, Technical Report No. 26. 21 pages.

McCaw, W. L. and R. H. Smith. 1992. Seed release from *Banksia baxteri* and *Hakea crassifolia* following scrub-rolling and burning. Journal of the Royal Society of Western Australia 75: 47-50.

McCaw, L. and K. Gillen. 1993. Fire management. In: The Stirling Range - a natural history (edited by C. Thompson, G. Hall, and G. Friend), Western Australian Department of Conservation and Land Management, Perth, pages 143-148.

McCaw, W. L., J. E. Neal, and R. H. Smith. 1996. Fuel accumulation following prescribed burning in young even-aged stands of karri (*Eucalyptus diversicolor*). Australian Forestry 59: 171-177.

McCaw, W. L. and E. A. Catchpole. 1997. Comparison of grass fuel moisture contents predicted using the McArthur Mark V Grassland Fire Danger Meter and an equation derived from the meter. Australian Forestry 60: 158-160.

McCormick, J. 1966. A note on scrub burning. Western Australian Forests Department, Forest Notes 4(2): 25-27.

McLain, D. H. 1974. Drawing contours from arbitrary data points. The Computer Journal 17: 318-324.

Mooney, H. A. and C. E. Conrad (editors). 1977. Symposium on the environmental consequences of fire and fuel management in mediterranean ecosystems. United States Department of Agriculture, Forest Service, General Technical Report WO-3, Washington. 498 pages.

Mount, A. B. 1972. The derivation and testing of a soil dryness index using run-off data. Tasmanian Forestry Commission Bulletin No. 4. 31 pages.

Muller, C. 1993. Wildfire threat analysis - an effective decision support system for fire protection planning. In: The burning question - fire management in NSW (edited by J. Ross), University of New England, Coffs Harbour, August 5-7, 1993, pages 103-114.

Naveh, Z. and R. H. Whittaker. 1979. Structural and floristic diversity of shrublands and woodlands in northern Israel and other mediterranean areas. Vegetatio 41: 171-190.

Nelson, R. M. (Jr.) 1984. A method for describing equilibrium moisture content of forest fuels. Canadian Journal of Forest Research 14: 597-600.

Nelson, R. M. 1991. A model of diurnal moisture change in dead forest fuels. In: Proceedings of the 11th Conference on Fire and Forest Meteorology, April 16-19 1991, Missoula, Society of American Foresters, Bethesda MD, pages 109-116.

Nelson, R. M. and C. W. Adkins. 1986. Flame characteristics of wind-driven surface fires. Canadian Journal of Forest Research 16: 1293-1300.

Nesterov, V. G. 1949. Combustibility of the forest and methods for its determination. USSR State Industry Press, 1949.

Noble, J. C., A. W. Smith, and H. W. Leslie. 1980. Fire in the mallee shrublands of western New South Wales. Australian Rangelands Journal 2: 104-114.

Noble, I. R. and R. O. Slatyer. 1981. Concepts and models of succession in vascular plant communities subject to recurrent fire. In: Fire and the Australian biota (edited by A. M. Gill, R. H. Groves, and I. R. Noble), Australian Academy of Sciences, Canberra, pages 311-338.

Noble, I. R., G. A. V. Bary, and A. M. Gill. 1980. McArthur's fire danger meters expressed as equations. Australian Journal of Ecology 5: 201-203.

O'Connell, A. M. 1987. Litter dynamics in karri (*Eucalyptus diversicolor*) forests of south-western Australia. Journal of Ecology 75: 781-796.

Olsen, J. S. 1963. Energy storage and the balance of producers and decomposers in ecological systems. Ecology 44: 95-111.

Olson, C. M. 1980. An evaluation of the Keetch-Byram drought index as a predictor of foliar moisture content in a chaparral community. In: Proceedings of the Sixth Conference on Fire and Forest Meteorology, Society of American Foresters and American Meteorological Society, Seattle, April 22-24, 1980, pages 241-245.

Paysen, T. E. and J. D. Cohen. 1990. Chamise chaparral dead fuel fraction is not reliably predicted by age. Western Journal of Applied Forestry 5: 127-131.

Peet, G. B. 1971. Fires studies in jarrah (*Eucalyptus marginata* Sm.) forest. Unpublished Master of Science Thesis, School of Forestry, University of Melbourne, 161 pages.

Philpot, C. W. 1963. The moisture content of Ponderosa Pine and Whiteleaf Manzanita foliage in the Central Sierra Nevada. United States Department of Agriculture, Forest Service, Research Note PSW-39, Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 7 pages.

Philpot, C. W. 1965. Diurnal fluctuation in moisture content of Ponderosa Pine and Whiteleaf Manzanita leaves.United States Department of Agriculture, Forest Service, Research Note PSW-67, Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 7 pages.

Philpot, C. W. 1969. Seasonal changes in heat content and ether extractive content of chamise. United States Department of Agriculture, Forest Service, Research Paper INT-61, Intermountain Research Station, Ogden, Utah. 10 pages.

Philpot, C. W. and R. W. Mutch. 1971. The seasonal trends in moisture content, ether extractives and energy of Ponderosa Pine and Douglas Fire needles. United States Department of Agriculture, Forest Service, Research Paper INT-102, Intermountain Research Station, Ogden, Utah. 21 pages.

Pirsko, A. R. and L. R. Green. 1967. Record low fuel moisture follows drought in Southern California. Journal of Forestry 65(9): 642-643.

Pompe, A. and R. G. Vines. 1966. The influence of moisture on the combustion of leaves. Australian Forestry 30: 231-241.

Pook, E. W. 1993. Empirical models evaluated for prediction of fine fuel moisture in Australian *Pinus radiata* plantations. New Zealand Journal of Forestry Science 23: 278-297.

Powell, T. L. 1974. Evaluation of a weighted disc meter for pasture yield estimation on intensively stocked dairy pasture. New Zealand Journal of Experimental Agriculture 2: 237-41.

Pyne, S. J. 1984. Introduction to wildland fire - fire management in the United States. John Wiley and Sons, New York. 455 pages.

Rawson, R. 1982. Fire behaviour. In: Fire ecology in semi-arid lands (edited by A. Hieslers, P. Lynch and B. Walters), Proceedings of a workshop held at Mildura, Victoria 24-29 May 1981, sponsored by the Council of Nature Conservation Ministers.

Raison, R. J., P. V. Woods and P. K. Khanna. 1983. Fuel dynamics in recurrently burnt eucalypt forests. Australian Forestry 46: 294-302.

Riggan, P. J., S. E. Franklin, J. A. Brass and F. E. Brooks. 1995. Perspectives on fire management in mediterranean ecosystems of southern California. In: The role of fire in mediterranean-type ecosystems (edited by J. M. Moreno and W. C Oechel), Springer-Verlag. 201 pages.

Rothermel, R. C. 1972. A mathematical model for predicting fire spread in wildland fuels. United States Department of Agriculture, Forest Service, Research Paper INT-115, Intermountain Research Station, Ogden, Utah. 40 pages.

Rothermel, R. C. 1991. Predicting behavior and size of crown fires in the Northern Rocky Mountains. United States Department of Agriculture, Forest Service, General Research Paper INT-438, Intermountain Research Station, Ogden, Utah. 46 pages.

Rothermel, R. C. and C. W. Philpot. 1973. Predicting changes in chaparral flammability. Journal of Forestry 71: 640-643.

SAS Institute Inc. 1985. SAS Users guide: Statistics, Version 5 Edition. Cary, North Carolina. 956 pages.

Schneider, B. H. and D. T. Bell. 1985. A simple, effective technique for rapid measurement of fuels in low shrub communities. Australian Forest Research 15: 79-84.

Semenuik, V. 1993. Geology, landform, soils and hydrology. In: The Stirling Range - a natural history (edited by C. Thompson, G. Hall, and G. Friend), Western Australian Department of Conservation and Land Management, Perth, pages 13-26.

Simard, A. J. 1968. The moisture content of forest fuels - 1. A review of the basic concepts. Canadian Department of Forest and Rural Development, Forest Fire Research Institute, Information Report FF-X-14, Ottawa, Ontario. 47 pages.

Simard, A. J., J. A. Eenigenburg, K. B. Adams, R. L. Nissen, and A. G. Deacon. 1984. A general procedure for sampling and analyzing wildland fire spread. Forest Science 30 (1), 51-64.

Sneeuwjagt, R. J. 1971. Understorey fuels in karri forest. Forests Department of Western Australia, Research Paper Number 1.

Sneeuwjagt, R. J. and G. B. Peet. 1985. Forest fire behaviour tables for Western Australia. Western Australian Department of Conservation and Land Management, Perth.

Specht, R. L. 1966. The growth and distribution of mallee-broombush (*Eucalyptus incrassata-Melaleuca uncinata*) and heath vegetation near Dark Island Soak, Ninety-Mile Plain, South Australia. Australian Journal of Botany 14: 361-371.

Specht, R. L. 1969. A comparison of the sclerophyllous vegetation characteristics of the mediterranean type climates in France, California and southern Australia. 2. Dry matter, energy and nutrient accumulation. Australian Journal of Botany 17: 293-308.

Specht, R. L. 1970. Vegetation. In: The Australian Environment (edited by G. W. Leeper, 4th edition) Commonwealth Scientific and Industrial Research Organisation and University of Melbourne Press, Melbourne, Australia, pages 44-67.

Specht, R. L. 1981. Responses to fires in heathlands and related shrublands. In: Fire and the Australian Biota (edited by A. M. Gill, R. H. Groves and I. R. Noble), Australian Academy of Science, Canberra, Australian Capital Territory, pages 395-416.

SYSTAT, Inc. 1992. SYSTAT for Windows: Graphics, Version 5 Edition. Evanston, Illinios. 636 pages.

Thomas, P. H. 1963. The size of flames from natural fires. Ninth Symposium (International) on Combustion, The Combustion Institute, pages 844-859.

Thomas, P. H. 1970. The rates of spread of head fires in gorse and heather. FR Note Number 796, Joint Fire Research Organisation, Ministry of Technical and Fire Office’s Commission.

Thomas, P. H. 1971. Rates of spread of some wind-driven fires. Forestry XLIV (2), 155-175.

Trabaud, L. 1979. Etude du comportement de feu dans la Garrigue de Chene kermes a' partir des temperatures et des vitesses de propagation. Annales des Sciences forestie'res 36 (1): 13-38.

Tunstall, B. 1991. Live fuel water content. In: Proceedings of a Conference on Bushfire Modelling and Fire Danger Rating Systems (edited by N. P. Cheney and A. M. Gill), Commonwealth Scientific and Industrial Research Organisation, Canberra, pages 127-136.

Valette, J. C., B. Sol, and C. Moro. 1994. Flammability parameters and soil water reserve to improve the forecast of the meteorological forest fire danger index. In: Proceedings of the Second International Conference on Forest Fire Research, Coimbra, Portugal, Volume II, Section C.08, pages 611-624.

Van Wagner, C. E. 1967(a). Calculations on forest-fire spread by flame radiation. Canada Department of Forestry and Rural Development, Forestry Branch, Departmental Publication Number 1185.

Van Wagner, C. E. 1967(b). Seasonal variation in moisture content of Eastern Canadian tree foliage and the possible effect on crown fires. Canada Department of Forestry and Rural Development, Forestry Branch, Departmental Publication Number 1204. 15 pages.

Van Wagner, C. E. 1969. Combined effect of sun and wind on surface temperature of litter. Canadian Forestry Service, Information Report PS-X-10, Petawawa Forest Experiment Station, Chalk River, Ontario. 4 pages.

Van Wagner, C. E. 1972. Equilibrium moisture contents of some fine forest fuels in eastern Canada. Canadian Forestry Service, Information Report PS-X-36, Petawawa Forest Experiment Station, Chalk River, Ontario. 11 pages.

Van Wagner, C. E. 1977a. Conditions for the start and spread of crown fires. Canadian Journal of Forest Research 7: 23-34.

Van Wagner, C. E. 1977. A method of computing fine fuel moisture content throughout the diurnal cycle. Canadian Forest Service, Information Report PS-X-69, Petawawa Forest Experiment Station, Chalk River, Ontario. 9 pages.

Van Wagner, C. E. 1979. A laboratory study of weather effects on the drying rate of jack pine litter. Canadian Journal of Forest Research 9: 267-275.

Van Wagner, C. E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forestry Service, Forestry Technical Report 35. 37 pages.

Van Wilgen, B. W. 1981. Some effects of fire frequency on fynbos plant community composition and structure at Jonkershoek, Stellenbosch. South African Forestry Journal 118: 42-55.

Van Wilgen, B. W. 1982a. Some effects of post-fire age on the above-ground plant biomass of fynbos (macchia) vegetation in South Africa. Journal of Ecology 70: 217-225.

Van Wilgen, B. W. 1982b. Some effects of fire frequency on fynbos plant community composition and structure at Jonkershoek, Stellenbosch. South African Forestry Journal 118: 42-55.

Van Wilgen, B. W. 1984. Adaptation of the United States Fire Danger Rating System to fynbos conditions. Part 1. A fuel model for fire danger rating in the fynbos biome. South African Forestry Journal 129: 61-65.

Van Wilgen, B. W., D. C. Le Maitre, and F. J. Kruger. 1985. Fire behaviour in South African fynbos (macchia) vegetation and predictions from Rothermel's fire model. Journal of Applied Ecology 22: 207-216.

Van Wilgen, B. W., K. B. Higgins, and D. U. Bellstedt. 1990. The role of vegetation structure and fuel chemistry in excluding fire from forest patches in the fire-prone fynbos shrublands of South Africa. Journal of Ecology 78: 210-222.

Viegas, D. X., M. T. Viegas, and A. D. Ferreira. 1992. Moisture content of fine forest fuels and fire occurrence in central Portugal. International Journal of Wildland Fire 2(2): 69-86.

Vines, R. G. 1981. Physics and chemistry of rural fires. In: Fire and the Australian Biota (edited by A. M. Gill, R. H. Groves and I. R. Noble), Australian Academy of Science, pages 129-150.

Viney, N. R. 1991. A review of fine fuel moisture modelling. International Journal of Wildland Fire 1: 215-234.

Viney, N. R. 1992. Modelling fine fuel moisture content. Unpublished Doctoral Thesis, Department of Mathematics, University College, University of New South Wales. 137 pages.

Viney, N. R and T. J. Hatton. 1989. Assessment of existing fine fuel moisture models applied to *Eucalyptus* litter. Australian Forestry 52: 82-93.

Wardell-Johnson, G., W. L. McCaw, and K.G. Maisey. 1989. Critical data requirements for effective management of fire on nature conservation lands in south-western Australia. In: Fire management on nature conservation lands (edited by N. Burrows, L. McCaw and G. Friend). Western Australian Department of Conservation and Land Management Occasional Paper 1/89, pages 59-74.

Weise, D. R., D. E. Ward, T. E. Paysen, and A. L. Koonce. 1991. Burning California chaparral - An exploratory study of some common shrubs and their combustion characteristics. International Journal of Wildland Fire 1(3): 153-158.

Weise, D. R. and G. S. Biging. 1996. Effects of wind velocity and slope on flame properties. Canadian Journal of Forest Research 26 (10): 1849-1858.

Wilson, A. A. G. 1992. Eucalypt bark hazard guide. Department of Conservation and Environment, Victoria, Fire Management Branch, Research Report Number 32. 16 pages.

Wills, R. 1992. The ecological impact of *Phytophthora cinnamomi* in the Stirling Range National Park. Australian Journal of Ecology 17: 145-159.

Witkowski, E. T. F., B. B. Lamont, and S. J. Connell. 1991. Seed bank dynamics of three co-occurring *Banksias* in south coastal Western Australia: the role of plant age, cockatoos and interfire establishment. Australian Journal of Botany 39: 385-397.

Zar, J. H. 1984. Biostatistical analysis. Second Edition. Prentice-Hall, New Jersey. 718 pages.

APPENDIX A

List of vascular plants recorded in fourteen 10 m x 10 m quadrats prior to experimental burning of 20-year-old mallee-heath. Also shown are the number of quadrats in which each taxa was recorded, the modal cover rating, and the height class in which the taxa most commonly occurred. Cover rating categories are as follows: (1) plants rare, <1 per cent cover, (2) any number of plants with <1 per cent cover, (3) Any number with 1-5 per cent cover, (4) any number with 5-10 per cent cover, (5) any number with 10-25 per cent cover.

Family	Taxon	No. of quadrats recorded in	Modal cover rating	Height Stratum (m) 0 - 0.4	0.4 - 1	1 - 2	>2
MONOCOTYLEDONS							
Anthericaceae	*Laxmania brachyphylla* F. Muell.	10	2	*			
	Thysnathotus sparteus R. Br.	2	1/2	*			
Cyperaceae	*Lepidosperma angustatum* R. Br.	6	2	*			
	Mesomelaena stygia subsp. *stygia* (R. Br.) Nees	14	3	*			
	Schoenus brevisetis R. Br.	5	2	*			
Dasypogonaceae	*Calactasia cyanea* R. Br.	2	2	*			
	Lomandra #32	6	2	*			
Xanthorrhoeaceae	*Xanthorrhoea platyphylla* D J Bedford	14	3			*	
Haemodoraceae	*Conostylis setigera* R. Br	13	2	*			
Iridaceae	*Orthrosanthus laxus* Benth.	9	2	*			
Orchidaceae	*Caladenia flava* R. Br.	2	1	*			
Restionaceae	*Loxocarya* sp. *nova*	12	2	*			
	Restio sphaecelatus R. Br.	13	3	*			
DICOTYLEDONS							
Casuarinaceae	*Allocasuarina humilis* L. Johnson	13	3		*		
	Allocasuarina thuyoides (Miq.) L. Johnson	11	3		*		
Dilleniaceae	*Hibbertia lineata* Steudel in Lehm.	13	3		*		
Droseraceae	*Drosera* #101	3	1	*			
Epacridaceae	*Andersonia simplex* Druce.	8	2	*			
	Astroloma baxteri D.C.	4	2	*			
	Astroloma drummondii Sonder in Lehm.	3	2	*			
	Astroloma tectum R. Br.	9	2	*			
	Leucopogon cucullatus R. Br.	2	2		*		
	Leucopogon gibbosus Stschegl.	13	3		*		
	Lysinema ciliatum R. Br.	7	2		*		

Family	Taxon	No. of quadrats recorded in	Modal cover rating	Height Stratum (m) 0 - 0.4	0.4 - 1	1 - 2	>2
Epacridaceae (cont.)	*Monotoca oligarrhenoides* F. Muell	2	2	*			
	Oligarrhena micrantha R. Br.	2	2	*			
Fabaceae	*Burtonia scabra* (Smith) R. Br.	1	2	*			
	Chorizema diversifolium D.C.	10	2		*		
	Daviesia inflata M.D. Crisp	6	3		*		
	Daviesia oppositifolia Endl.	2	2/4		*		
	Gompholobium knightianum R.Br.	2	1/2	*			
	Hovea pungens Benth. in Endl.	2	2		*		
	Jacksonia grevilleoides Turcz.	1	2			*	
	Gastrolobium velutinum E. Pritzel	11	4		*		
	Pultenea ericoides Schauer in Lehm.	13	3/4		*		
	Sphaerolobium vimineum Smith	2	2	*			
Goodeniaceae	*Dampiera juncea* Benth.	12	2	*			
	Goodenia caerulea R. Br.	1	2	*			
	Leschenaultia formosa R. Br.	5	1	*			
Loganiaceae	*Logania serpyllifolia* R. Br.	2	2	*			
Lauraceae	*Cassytha pomiformis* Nees.	1	2	*			
Mimosaceae	*Acacia squamata* Lindley	1	1		*		
	Acacia biflora R. Br.	7	2		*		
	Acacia browniana H. L. Wendl.	5	2		*		
Myrtaceae	*Agonis spathulata* Schauer in Lehm.	14	3		*		
	Baeckea pachyphylla Benth.	6	3		*		
	Beaufortia empetrifolia Schauer	2	2		*		
	Beaufortia schaueri Preiss ex Shauer	14	4		*		
	Calothamnus affinis var. teres Turcz.	5	3		*		
	Calothamnus gracilis R. Br.	1	3		*		
	Calothamnus sanguineus Labill.	7	2		*		
	Calytrix leschenaultii (Schauer) Benth.	2	1/2	*			
	Calytrix flavescens Cunn.				*		
	Conothamnus aureus Turcz. (Domin)						
	Darwinia vestita Benth.	10	2		*		
	Eucalyptus decipiens Endl.	6	3				*
	Eucalyptus marginata Donn ex Sm.	3	3				*

Family	Taxon	No. of quadrats recorded in	Modal cover rating	Height Stratum (m) 0 - 0.4	0.4 - 1	1 - 2	>2
Myrtaceae (cont.)	*Eucalyptus pachyloma* Benth.	14	4/5				*
	Eucalyptus tetragona F. Muell.	12	3				*
	Leptospermum spinescens Endl.	4	2/3		*		
	Melaleuca pentagona Labill.	13	3		*		
	Verticordia densiflora Lindley	1	1	*			
Proteaceae	*Adenanthos cuneatus* Labill	1	1		*		
	Banksia gardneri var gardneri A.S. George	11	3	*			
	Banksia nutans var nutans R. Br.	2	3		*		
	Banksia sphaerocarpa R. Br.	13	3		*		
	Conospermum #83	1	2	*			
	Dryandra armata var armata R. Br.	11	3		*		
	Dryandra armata var nova R. Br.	8	3			*	
	Dryandra cuneata R. Br.	7	2/3		*		
	Dryandra brownii Meissner	14	3	*			
	Dryandra drummondii Meissner	14	5	*			
	Dryandra blechnifolia R. Br.	2	2/3	*			
	Dryandra sessilis var sessilis Domin	7	3			*	
	Dryandra tenuifolia var tenuifolia R. Br.	2	2	*			
	Grevillea fasiculata R. Br.	4	2	*			
	Hakea ambigua Meissner	11	3		*		
	Hakea corymbosa R. Br.	5	3		*		
	Hakea crassifolia Meissner	13	3				*
	Hakea ruscifolia Labill	6	3			*	
	Hakea trifurcata R. Br.	12	3		*		
	Hakea varia R. Br.	1	3			*	
	Isopogon formosus R. Br.	13	2			*	
	Isopogon latifolius R. Br.	4	2	*			
	Isopogon tripartitus R. Br.	7	2		*		
	Lambertia inermis R. Br.	12	4				*
	Petrophile ericifolia R. Br.	5	2			*	
	Petrophile longifolia R. Br.	14	3	*			
	Petrophile phylicoides R. Br.	9	2			*	

Family	Taxon	No. of quadrats recorded in	Modal cover rating	0 - 0.4	0.4 - 1	1 - 2	>2
Proteaceae (cont.)	*Petrophile squamata* R. Br.	14	3			*	
	Petrophile serruriae R. Br.	4	3			*	
	Stirlingia latifolia Steudel	4	2/3	*			
	Stirlingia anethifolia (R. Br.) Endl.	3	3	*			
	Synaphea preissii Meissner	7	2	*			
Pittosporaceae	*Billardiera bicolor* E. M. Bennett	10	2	*			
Rutaceae	*Boronia inconspicua* Benth.	10	2	*			
	Boronia spathulata Lindley	6	2	*			
Stylidiaceae	*Stylidium imbricatum* Benth.	2	1	*			
	Stylidium repens R. Br.	2	1	*			
	Stylidium #25	2	1	*			
	Stylidium #26	8	2	*			
	Stylidium #27	3	1	*			

APPENDIX B

Commonly used symbols and abbreviations

Abbreviations

CBEF	McArthur Control Burning in Eucalypt Forests guide
EMC	Equilibrium moisture content
FFBT	Forest Fire Behaviour Tables for Western Australia
FFDM	McArthur Forest Fire Danger Meter (Mark V)
FFMC	Fine Fuel Moisture Code (from the Canadian Fire Weather Index)
GFDM	McArthur Grassland Fire Danger Meter (Mark IV or V)
ISI	Initial Spread Index
JFDI	Jarrah Forest Fire Danger Index
KBDI	Keetch Byram Drought Index
SDI	Soil Dryness Index
SMC	Surface Moisture Content for *Eucalyptus marginata* litter

Symbols

d	Particle thickness, mm.
F_H	Flame height, m.
F_L	Flame length, m.
h	Fuel low heat of combustion, kJ kg^{-1}.
H	Fractional relative humidity.
I_B	Byram's fireline intensity, kW m^{-1}.
L	Fuel loading, kg m^{-2}.
m	Molecular weight of water, g mol^{-1}.
M	Fuel moisture content, per cent.
M_e	Equilibrium moisture content, per cent.
M_{de}	Moisture content of dead elevated fine fuel, per cent.
M_{fo}	Moisture content of live foliage (*Dryandra drummondii*), per cent
M_{ld}	Moisture content of deep litter under mallee clumps, per cent.
M_{ls}	Moisture content of shallow litter under low shrubs, per cent.
MC_{ex}	Moisture content of extinction in BEHAVE model, per cent.
r	Fuel particle response time
R	Forward rate of spread, m s^{-1}.
RH	Relative humidity, per cent.
t	Time since fire, years.
T	Air temperature, °C
S	Solar radiation, W m^{-2}
U	Wind speed, m s^{-1}.

APPENDIX C

Wind speed profiles in mallee-heath vegetation

Introduction

Wind speed typically increases with height above ground according to a logarithmic profile (Albini and Baughmann 1979). In Australia, the standard exposure height of surface wind instruments over level open terrain is 10 m above ground, where open terrain is defined as an area where the distance between the instrument and any obstruction is at least ten times the height of the obstruction (Anonymous 1975). A range of methods have been developed to allow the prediction of wind speed at a given height from wind speed measured at, or forecast for a different height, most commonly for standard exposure conditions. These methods include simple correction factors and linear regression equations (Sneeuwjagt and Peet 1985, Cheney *et al.* 1987), logarithmic extrapolation (Albini and Baughmann 1979), and more complex equations taking into account atmospheric stability considerations (Durre and Beer 1989).

Relationship between wind speed at 10 m height and 2 m height in open terrain

During the experimental fires conducted at the Stirling Range wind speed in the open was measured both at 10 m (U_{10}) and 2 m (U_2) height above ground. In several instances the 10 m height instrument malfunctioned immediately prior to, or during an experimental fire. To be able to use the data from the 2 m instrument to predict the wind speed at 10 m above ground the relationship between wind speed at the different heights had to be established. While theoretical or empirical methods developed in other studies could have been applied, it was considered preferable to establish the relationship between U_{10} and U_2 for the particular conditions of the study. This relationship was developed using wind speed data collected during a period of 15.5 hours on 19 and 20 February 1991. Weather during the sampling period was warm to hot with air temperatures ranging from 24°C and 39°C, and peak global solar radiation of 800-850 W m^{-2} each day.

Wind speed was recorded using a UNIDATA anemometer mounted at 10 m height on a portable pump-up mast and an identical anemometer at 2 m height on a stand located about 5 m away from the mast. Instruments were sited in the centre of a 100 m wide strip that had been scrub-rolled and burnt 20 months previously and carried only sparse vegetation less than 0.2 m in height. Data loggers used for the study captured the raw wind speed data as means over 30 second intervals. Prior to analysis, raw data were combined into mean values over 10 minutes to reduce the extent of variability. The mean and range of wind speed data at each height are shown in Table C.1.

TABLE C.1

Descriptive statistics for wind speed data collected on 19 and 20 February 1991 using anemometers placed at 2 m and 10 m height above ground in open terrain. Data represent mean wind speeds recorded over a 10 minute period (n = 93).

Height of instrument (m)	U (m s^{-1}) Mean	Minimum	Maximum
2	3.6	2.0	6.5
10	5.1	2.4	9.3

A scatterplot of U_2 and U_{10} m height indicated a strong linear relationship between the two variables (Figure C.1). There were several outliers in the data set but these did not affect the overall form of the relationship between the variables.

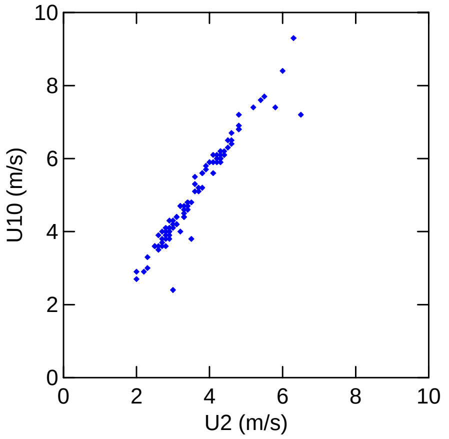


Figure C.1 Scatterplot showing corresponding values of U_2 and U_{10} for open exposure conditions.

Linear regression equations describing U_{10} as a function of U_2 were fitted to the data, both with and without constants. Equivalent equations describing U_2 as a function of U_{10} were also fitted. The goodness of fit of equations was judged according to scatterplots of residuals and the root mean square error (RMSE) defined as $(\Sigma_i(U - U')^2/n)^{0.5}$ where U and U' are respectively the observed and fitted values for wind speed. Values of r^2 for equations fitted without constants are not directly comparable with those for equations with constants because total sums of squares were calculated by a different formula (SYSTAT 1992). For the equations without constants r^2 was defined as $1 - \Sigma(U - U')^2/\Sigma U^2$ (Klavseth 1985). Equations are presented in Table C.2.

All equations provided a good fit to the data (r^2 >0.93)with a normal distribution of residuals. The constant in equation C.4 was not significantly (P>0.05) different from zero, indicating that the regression line passed through the origin, but the constant in equation C.2 was significantly different to zero. There was little difference in the RMSE for each pair of equations.

TABLE C.2

Statistics for equations relating U_2 to U_{10} in open conditions. Coefficents and the RMSE for each equation are shown.

	Equation	Coefficent		r^2	RMSE
		a	b		
(C.1)	$U_2 = b\ U_{10}$	-	0.71	0.99	0.252
(C.2)	$U_2 = a + b\ U_{10}$	0.22 (P=0.03)	0.67	0.93	0.247
(C.3)	$U_{10} = b\ U_2$	-	1.39	0.99	0.352
(C.4)	$U_{10} = a + b\ U_2$	0.03 (n.s.)	1.39	0.93	0.354

Cheney *et al.* (1987) developed an equation of similar form to describe the relationship between U_2 and U_{10} above tropical grassland at Annaburroo in the Northern Territory. Relationships developed for mallee-heath and tropical grassland are compared in Figure C.2.

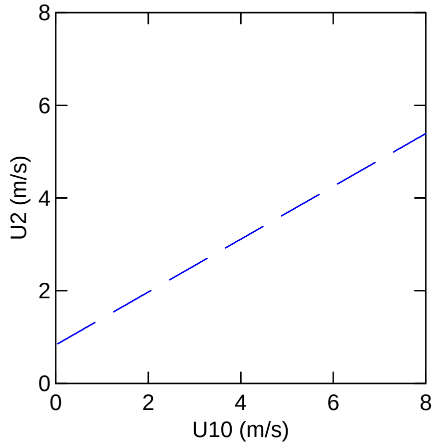


Figure C.2 Linear functions relating U_2 to U_{10} for open exposure conditions in mallee-heath (this study) and tropical grassland (Cheney *et al*. 1987). Functions for mallee-heath are indicated by continuous lines and the tropical grassland function by the dashed line.

Relationship between wind speed at 10 m height in the open and at 2 m and 0.5 m height within mallee-heath vegetation

A separate study was undertaken to compare the wind speed at 0.5 m and 2 m height in standing mallee-heath vegetation with U_{10} at standard exposure conditions, this being the normal situation for which wind speed forecasts are provided. The aim of this study was to determine the extent to which wind speed was reduced by the vegetation. Some fire behaviour models use wind speed at 1.5 m or 2.0 m height within standing vegetation as an input variable, for example the jarrah forest fire spread model of Burrows (1994).

Data for this study were collected over a 16 hour period between 1600 hours on 29 October and 0800 hours on 30 October 1990. Weather during the sampling period was cool with air temperatures between 8 and 14°C, and global solar radiation below 400 W m^{-2}. An anemometer was mounted at 10 m height on a tower that was located in the centre of the 100 m wide scrub-rolled strip described in the previous section. Anemometers were also mounted at 0.5 m and 2 m height within an adjacent stand of 20-year-old mallee-heath that was representative of the height and structure of the vegetation at the experimental site. The anemometers in the the mallee-heath were approximately 100 m away from the base of the tower, and at least 50 m away from the edge of the track that demarcated the scrub-rolled strip. As in the previous analysis raw data from the loggers were combined into mean values over 10 minutes. The mean and range of wind speed data at each height are shown in Table C.3.

TABLE C.3

Descriptive statistics for wind speed data collected using anemometers placed at 0.5 m and 2 m within mallee-heath vegetation and at 10 m height above ground in open terrain. Data represent mean wind speed recorded over a 10 minute period (n = 95).

Height of instrument (m)	U (m s^{-1}) Mean	Minimum	Maximum
0.5	0.3	0	0.9
2	1.4	0.1	3.2
10	4.1	1.4	7.6

Mean wind speeds at 0.5 m height were substantially less than those at 2 m height, and in some cases the wind speed at 0.5 m was insufficient to activate the anemometer (Table C.3). Scatterplots indicated that relationships between wind speed at 10 m and at 0.5 m and 2 m within height within the vegetation were linear (Figure C.3).

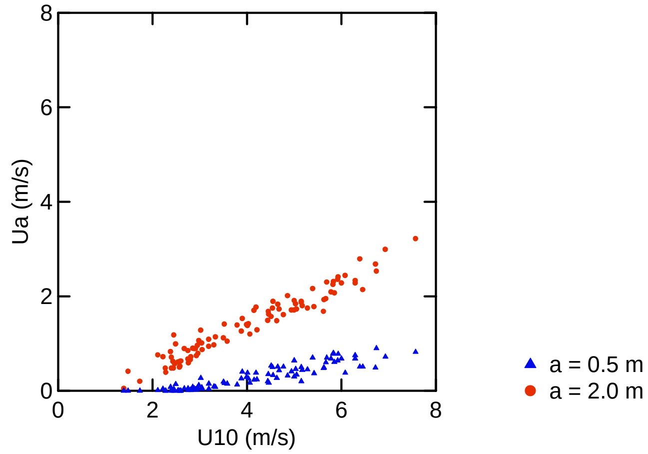


Figure C.3 Scatterplot showing relationship between U_{10} at open exposure conditions and U_a at two heights (0.5 m and 2.0 m) in 20-year-old mallee-heath.

Linear regression equations describing U_2 and $U_{0.5}$ as a function of U_{10} were fitted to the data, both with and without constants (Table C.4).

TABLE C.4

Statistics for equations relating U_{10} at open exposure conditions to U_2 and $U_{0.5}$ in 20-year-old mallee-heath. Coefficents and the RMSE for each equation are shown.

	Equation	Coefficent		r^2	RMSE
		a	b		
(C.5)	$U_2 = b\ U_{10}$	-	0.36	0.98	0.229
(C.6)	$U_2 = a + b\ U_{10}$	-0.45 ($P<0.01$)	0.46	0.94	0.170
(C.7)	$U_{0.5} = b\ U_{10}$	-	0.08	0.82	0.165
(C.8)	$U_{0.5} = a + b\ U_{10}$	-0.38 ($P<0.01$)	0.16	0.84	0.105

Regression equations relating U_2 to U_{10} had higher r^2 values than those for equations relating $U_{0.5}$ to U_{10}. The poorer fit of the equation for U_2 reflects the greater influence of the vegetation on the windfield close to ground level and is consistent with theoretical considerations of how windfields are affected by surface roughness (Garratt 1980). Equations fitted with constants had lower root mean square errors than those fitted without constants. Residuals from the equations fitted with constants were normally distributed, while those from equations fitted without constants were strongly skewed, indicating a biased fit to the data.

APPENDIX D

Wildfires in the Fitzgerald River National Park, Western Australia, December 1989

McCaw, L., T. Maher and K. Gillen

Published as Technical Report No. 26
Department of Conservation and Land Management
Perth, Western Australia
April 1992

Figure 2.8 (a) Bulk density of the fuel bed in four height classes for consecutive 1m ^{2} quadrats along five fuel sampling transects in Plot C. Figures at the base of each column indicate the percentage cover of litter within the quadrat.

Figure 2.8 (b) Bulk density of the fuel bed in four height classes for consecutive 1m ^{2} quadrats along five fuel sampling transects in Plot I. Figures at the base of each column indicate the percentage cover of litter within the quadrat.

Figure 4.13 (a) Histograms showing the extent of litter consumption resulting from three different categories of fire spread, as defined in Section 4.5.12. The extent of fuel consumption following the initial lighting, and the final extent of fuel consumption following subsequent lightings are shown separately for conditional and non-sustaining fires. U/B indicates unburnt.

Figure 4.13 (b) Histograms showing the extent of dead fuel consumption in four height classes resulting from three different categories of fire spread, as defined in Section 4.5.12. The extent of fuel consumption following the initial lighting, and the final extent of fuel consumption following subsequent lightings are shown separately for conditional and non-sustaining fires. U/B indicates unburnt.

Figure 4.13 (b) continued **Figure 4.13 (b) continued**

Figure 4.13 (b) continued

Figure 4.13 (c) Histograms showing the maximum diameter of live fuel consumed in four height classes resulting from three different categories of fire spread, as defined in Section 4.5.12. The extent of fuel consumption following the initial lighting, and the final extent of fuel consumption following subsequent lightings are shown separately for conditional and non-sustaining fires. U/B indicates unburnt.

Figure 4.13 (c) continued **Figure 4.13 (c) continued**

Figure 4.13 (c) continued

Figure 4.14 Histograms showing consumption of litter, dead fuel and live fuel at sample points classified as either typical mallee-heath or sparse swamp vegetation in Plot C. Definitions of fire spread are as described in Figure 4.13.