# The Role of Fire in Governing the Relative Distribution of Rainforest and Sclerophyll Forest: the Effects of Rainforest Vegetation on Fire Spread.

**By**

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# Abstract

This project was undertaken to examine the potential importance of fire in governing the relative distribution of rainforest and sclerophyll forest, and the width and position of the boundary between them. Rainforest patches in south coastal N.S.W. were studied. The aim of the project was to use a general fire model to examine the factors important to suppressing fire in rainforest, that is to determine the effect of rainforest vegetation on certain key variables important to determining fire behaviour. Microclimates in the rainforest, sclerophyll forest and the boundary between were characterised and compared. It was shown that there are consistent differences in the microclimates of the vegetation types studied: the microclimate of the rainforest is more buffered from extremes in external conditions than sclerophyll forest or the boundary vegetation.

A litter moisture model was developed and used to examine the effect of altered microclimatic conditions and canopy cover on fuel drying in the different vegetation types. Modelling litter moisture shows that microclimatic conditions in the rainforest cause leaf litter to retain moisture for longer than litter in the other vegetation types. Work also focused on determining the possible effects of live rainforest and boundary vegetation on fire suppression. A leaf flammability experiment was conducted to test the ignitability of leaves from rainforest and sclerophyll species in a muffle furnace. An experimental burn was conducted to test the effect if vines, common to rainforest boundaries, have an effect on the forward progress of a fire burning through sclerophyll forest. Vegetation surveys were conducted at the line of extinguishment of past fires to examine if there were differences in the structure of the understorey vegetation between rainforest, rainforest boundaries and sclerophyll forest that may influence where fires of different intensities go out. This surveying and experimentation showed that differences in the nature of the live vegetation between rainforest, boundaries and sclerophyll forest directly contribute to the flammability of the vegetation.

By examining what suppresses fire in rainforest, and using the fire model to examine when rainforest is likely to burn, it is possible to gain insights into the importance of fire in determining the relative distribution of rainforest and sclerophyll forest in temperate areas, and in governing the position and width of rainforest boundaries. It was found that rainforest and rainforest boundaries will burn when litter moisture is very low, however, the flammability of rainforest and rainforest boundaries remains well below those of sclerophyll forest even during extreme fire weather and fuel dryness conditions. It is concluded that increasing the frequency of fire may impact upon rainforest distribution or the nature of the boundary. The techniques used in the study may be used for the control or prevention of fire in disturbed rainforest or in mixed vegetation containing rainforest. Information regarding the suppressive effect of vines may be useful to the identification of fire retardant vegetation for use in minimising damage to property and from bushfires.

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**Appendix 1**

# Section 1. Introduction

## 1.1. Project Overview and Aims

Broadly, there are two distinct forest types occurring in the wetter regions of eastern Australia, these are rainforests and sclerophyll forests which have an overstorey dominated by species of *Eucalyptus.* In temperate areas of eastern Australia, rainforest is distributed as patches within sclerophyll forest, occupying wetter sites such as gullies and south facing slopes (Webb and Tracey, 1981a,b; Helman, 1983, Yates, 1989, Barrett and Ash, 1992). These two forest types are composed of very different species associations and are structurally distinct (Howard, 1981; Webb and Tracey, 1981a,b). These differences lead to differences in flammability: closed forest types such as rainforest are less flammable than open sclerophyll forest (McArthur, 1967; Uhl and Kaufmann, 1990). Rainforest may be considered the climax community of phyrric succession in the tall open sclerophyll forests of south eastern Australia. Prolonged fire free periods are necessary for rainforest to become the dominant vegetation type (Cremer, 1960; Ashton, 1981a,b; Howard, 1981; Unwin *et al .,* 1985; Unwin, 1989). Past work has suggested that in certain topographic locations, rainforest and sclerophyll forest may not be in equilibrium but that there is a dynamic relationship in which distributions are determined by the impact of fire (Webb and Tracey, 1981b; Helman, 1983; Ash, 1988; Yates, 1989; Mullen, 1995). In places, rainforest may be restricted to positions offering microclimatic protection from fire (Webb and Tracey, 1981b; Yates, 1989, Mullen, 1995: Ash, 1988).

The relative importance of fire in limiting rainforest distribution compared with physiological factors is not well understood. The aim of this project is to examine differences in the flammability of rainforest and sclerophyll forest in order to better understand the influence of fire in governing the relative distribution of rainforest and sclerophyll forest in temperate areas. Differences in the flammability of rainforest and sclerophyll forest are examined by modelling fuel drying and potential fire spread in both forest types and in the boundary zone between the two. A general model incorporating the key variables that affect bushfire behaviour is used to examine how the rate of spread of fire would differ between the different forest types under the same set of external conditions. To use the fire model the effect of vegetation type on the key parameters must be determined. By modelling key factors it is possible to determine what causes fire to be suppressed in rainforest and, from weather records, the potential frequency of rainforest being burnt can be determined. By understanding what controls fire in rainforest, it is possible to gain insights into the influence of fire in controlling the relative distribution between rainforest and sclerophyll forest. If rainforest can be frequently burned, distribution may be very dependant on fire, if rainforest never burns then fire cannot limit distribution, and edaphic influences on plant growth must be stronger determinants of distribution.

This study is important because, in contrast to fire in flammable vegetation types such as eucalypt forest and pine forest, very little is known about what controls fire spread in relatively non-flammable vegetation types. In particular, there is very little research on the natural conditions which extinguish fire. This has implications regarding the management of fire for rainforest conservation (Gill, 1977), the conservation of rainforest being a concern worldwide. Understanding what limits fire spread in rainforest, or alternatively, when rainforest will burn, may also have significant implications in terms of the management of bushfires for the protection of property and life. The threat of bushfire in Australia has always been a critical issue. Following the devastating fires around Sydney in 1994, there has been renewed interest in identifying non-flammable species and vegetation types (Gill and Moore, 1996). This study should provide answers to questions about what causes fire suppression in rainforest. This study is also important for gaining a better understanding of how fire will move through a landscape, information that could be used when fighting or controlling bushfires. The fires in the rainforests of Indonesia occurring this year (1997) further highlight that rainforest will burn under certain circumstances, this study may shed light on the causes of this disaster and assist in preventing the same happening elsewhere in the world.

## 1.2. Characteristics of rainforest and sclerophyll forests

Rainforest is distinguished from eucalypt dominated forest on the basis of structure, range of lifeforms, floristic composition and response to disturbance, especially fire. Rainforests are closed forests which generally have a canopy cover >70%, usually >95%, which means light levels on the forest floor are only 2-3% of daylight (Cremer, 1960; Specht, 1981; Barrett and Ash, 1992). Sclerophyll forest is defined by the predominance of *Eucalyptus* species in the canopy. These share the characteristics of an open canopy and pendulous leaves allowing >15% of daylight to penetrate. Regeneration of *Eucalyptus* does not occur at light levels below 5-10% of daylight and so they are excluded from rainforest (Ashton, 1981a,b; Webb and Tracey, 1981a; Barrett and Ash, 1992; Adam, 1994). Rainforest communities are composed of shade tolerant plant species very different to those of the sclerophyll forest (Cremer, 1960; Webb and Tracey, 1981a,b). Rainforest canopy species are able to regenerate beneath an undisturbed canopy or in small canopy gaps, and are not dependant on fire for regeneration (Adam, 1994). Rainforests are characterised by the prominence of woody life forms such as epiphytes and lianas (Webb and Tracey, 1981b), the understorey is typically sparse with only scattered shrubs, seedlings and ferns. There is a notable absence in rainforest of understorey herbaceous monocots, such as sedges and grasses, that are common in open sclerophyll forest (Howard, 1981; Webb and Tracey, 1981b).

Rainforest in eastern Australia is distributed within 100 km of the coast from north Queensland to Tasmania where annual rainfall exceeds 800 mm (Webb and Tracey, 1981b). Continuous areas of rainforest only occur where annual rainfall exceeds 1500 mm. Throughout most of eastern Australia, rainforest exists as patches within the surrounding sclerophyll forest (Webb and Tracey, 1981a,b). Edaphic factors, often related to topography, are important in determining the distribution of rainforest in relation to the surrounding sclerophyll forest. Rainforest cannot exist in marginal areas on poorly structured or infertile soils except in topographic refuges where there are supplementary supplies of water and nutrients. (Webb and Tracey, 1981a,b). Typically, rainforest occupies small areas in gullies and on south facing slopes where the effects of solar radiation and desiccating winds on evaporation are reduced, soil moisture is increased and nutrients and soil accumulate from upslope (Webb and Tracey, 1981a,b, Helman, 1983; Yates, 1989). Past work has shown that the distribution of the two forest types in relation to each other is determined by the physiological responses of the different tree species to microclimatic conditions (Barrett and Ash, 1992).

Despite the microclimatic conditions governing the relative distribution of rainforest and sclerophyll forest, there is evidence that often, the distribution of these forest types is not in equilibrium, and that the position and width of the boundary zone between them may not be stable (Ashton, 1981a,b; Gill, 1981; Unwin *et al.*, 1985 Unwin, 1989; Mullen, 1995). Rainforest patches are surrounded by a boundary where rainforest seedlings disperse into the surrounding sclerophyll forest. This boundary may be extremely sharp, or there may be a broad transition between the two forest types. In the tropical north, where there is a pronounced annual dry season facilitating regular low-intensity fires, boundaries are narrow; in temperate areas boundary widths and distributions are more variable. There may be an extensive transition where rainforest dispersal leads to a continuous rainforest canopy under eucalypt emergents (Ashton, 1981a,b; Webb and Tracey, 1981a,b; Ash, 1988; Mullen, 1995), this has been termed mixed forest (Cremer, 1960). In places, extensive rainforest colonisation has lead to its existence in areas that would be considered marginal habitat for rainforest such as north facing slopes (Mullen, 1995). In other areas it can be observed that sites suitable for rainforest are often occupied by wet sclerophyll forest (Webb and Tracey, 1981a,b; Ashton, 1981a,b; Mullen, 1995).

Anomalies in the relative distribution of rainforest and sclerophyll forest in temperate Australia have a possible explanation in terms of an ecological interaction with fire. In Australia, bushfires are common and represent a powerful ecological force; many plant species have adapted to allow them to persist within a certain fire regime (Gill, 1975; Ashton, 1981b; Whelan, 1995). These responses are related to germination, seed storage, regeneration or increased growth in disturbed areas (Gill, 1975). Many species of the sclerophyll forest, in particular, *Eucalyptus*, have bark characteristics or regenerative responses, eg. lignotubers, allowing them to survive fire (McArthur, 1967) or recruit from seed after fire (Ashton, 1981a,b). There are very few non-flammable vegetation types in Australia, rainforest however, is relatively non-flammable.

Rainforest tree species have not evolved with frequent fire, and while they may regenerate well after a single fire, they are thin barked and repeated fires at short intervals may kill them (Ashton, 1981b; Stocker and Mott, 1981; Howard, 1981; Ash, 1988). Prolonged fire free periods may allow the expansion of rainforest into surrounding eucalypt forest, fire may impact upon rainforest distribution where rainforest is surrounded by sclerophyll forest (Cremer, 1960; Ashton, 1981a,b; Webb and Tracey, 1981a,b; Unwin *et al.*, 1985; Ash, 1988; Unwin, 1989).

The position and width of rainforest boundaries is determined by an interaction between moisture, nutrient availability, topography and fire which leads to site specific variation in boundary types (Ash, 1988). Fire may exert considerable control on the position and width of rainforest boundaries (Webb and Tracey, 1981a,b; Heiman, 1983; Ash, 1988; Yates, 1989; Mullen, 1995), variations in fire regime are expected to influence the stability of boundaries (Unwin *et al.*, 1985; Ash, 1988; Unwin, 1989). In comparison to the tropical north, there is far more variation in the frequency and intensity of fire in temperate Australia, and it is believed this may be responsible for the greater variation in rainforest distribution, and in the width and positions of rainforest ecotones (Unwin *et al.*, 1985; Ash, 1988; Unwin, 1989; Webb and Tracey, 1981a,b). Rainforest in south eastern Australia may be restricted to gullies and south facing slopes because these positions provide microclimatic protection from fuel drying and fire spread (Webb and Tracey, 1981b; Heiman, 1983; Ash, 1988; Yates, 1989; Mullen, 1995). The variation in boundary characteristics may be due to site specific differences in vulnerability to bushfires (Ash, 1988). The importance of fire in limiting the distribution of temperate rainforest in comparison with topographic effects on microclimate and nutrient status is not well understood. The key to understanding the relationship between rainforest and surrounding sclerophyll forest lies in determining the specific effects that rainforest vegetation may have on the spread of fire.

## 1.3. Modelling fire behaviour

The occurrence and behaviour of bushfires; whether they ignite, their intensity, and their rate of spread, is determined by the physical and chemical reactions of combustion. A simple fire model links fuel, moisture and oxygen as principle determinants of fire intensity (Luke and McArthur, 1978; Whelan, 1995). Bushfire behaviour is influenced by a complex interaction between a number of groups of factors operating at different scales. Topography and climate and the effect they have on the vegetation and fuel determine the likelihood of ignition and subsequent fire behaviour (Luke and McArthur, 1978; Cheney, 1981; Chandler *et al*., 1983; Whelan, 1995). Fire behaviour is ultimately determined by the amount of energy stored in the fuel. The most important fuel in forest fires is the fine dry litter on the forest floor. The availability of litter for consumption by fire is dependant upon its moisture content. Meteorological conditions affect both the possibility of ignition and fire behaviour. Time since rainfall, and conditions since rain will determine fuel moisture content. During a fire the most important meteorological variable influencing fire behaviour is wind speed. Wind speed is important because it both supplies oxygen and determines fuel preheating. The effects of topography are both direct and indirect. Direct effects include the influence of slope on fire behaviour and microclimatic effects on fuel drying. Topography has an indirect effect on fire behaviour because it directly affects the distribution of different vegetation types. The nature of the vegetation at a site will influence fire behaviour through affecting wind speed, fuel type and distribution, and microclimatic effects on fuel moisture (McArthur, 1967; Luke and McArthur, 1978; Whelan, 1995). The interaction between these determinants of fire behaviour is summarised in Figure 1.1.

Study of the factors controlling the behaviour of bushfires has lead to the development of methods for both measuring and predicting fire behaviour. There are various fire front characteristics that are used to describe and quantify fires, these include; the dimension and orientation of the flames, the rate of spread of a fire, the weight of the fuel consumed and the duration of flaming combustion (residence time). Certain measures are combined to derive expressions of the energy released by the fire eg. combustion rate and fire intensity (McArthur and Cheney, 1966; McArthur, 1967; Luke and McArthur, 1978; Cheney, 1981; Chandler *et al.*, 1983; Gill and Knight, 1988). The rate of forward spread of a fire is the most commonly used measurement of fire behaviour, and is relatively easy to estimate (McArthur and Cheney, 1966). Rate of spread can be combined with estimates of the weight of the fuel and the heat yield of the fuel to determine fire intensity.

The major factors affecting the behaviour of bushfires (see Figure 1.1) are well understood. This knowledge has been used to develop models and meters that predict the rate of spread and intensity of fires in a specific vegetation types (such as grassland and sclerophyll forest) from conditions in the open (Cheney, 1968; McArthur, 1967; Luke and McArthur, 1978; Noble *et al.*, 1980; Cheney, 1981; Crane, 1982, Chandler *et al.*, 1983). If the model is applied to a different vegetation type the effect of the key variables remains the same but the effect of the vegetation type on the parameters must be determined (McArthur, 1967; Luke and McArthur, 1978; Whelan, 1995). Equation 1.1 was used to estimate the rate of forward spread of fire spread (R, m $hr^{-1}$) from fuel load (F, kg $m^{-2}$), fuel moisture (M, wet weight/dry weight), wind speed (V, m $s^{-1}$), slope (S, degrees: + upslope, - downslope), and any possible suppressive effect of the live , vegetation (Z). The constants used are those derived from empirical study of fire in eucalypt forest (McArthur 1967), parameter values are determined from microclimatic differences between the forest types. Details about the specific effects on the key variables and how vegetation type will affect each are described in following paragraphs.

$$R = e^{\left(c_1 + \ln(F)\right) + c_2 V + c_3 S - \ln(Z) - c_4 M}$$

where $R$ = Rate of fire spread, m/hr
$F$ = Fuel dry wt, kg/$m^2$
$V$ = Wind velocity, m/sec
$S$ = Slope in direction of fire, ± degrees
Z = Foliage suppression effect
$M$ = Fuel moisture content, wet wt as proportion dry wt
$c_1=4.317$
$c_2=1.1$
$c_3=0.0693$
$c_4=20$

Equation 1.1: Fire spread equation.

The rate of forward spread and the intensity of a fire increases linearly with increases in fuel loads, fuel loads are determined by both the living and dead organic material available for consumption by fire (McArthur, 1967; Cheney, 1968; Luke and McArthur, 1978; Chandler *et al.,* 1983). The distribution and the average size of fuel may also be important as finer fuels that are well aerated ignite more quickly and because fuel may be distributed to allow fire to burn easily into the crowns of trees (Luke and McArthur, 1978). Leaf litter and other fine material on the forest floor is the most influential fuel component in most forest fires. Fuel loads are potentially lower in rainforest than in open forest because moist conditions allow for the rapid decomposition of ground litter and because rainforest leaves are thinner and decay faster than tough sclerophyllous litter (Howard, 1981; Whelan, 1995). There are also questions about how the nature of the live vegetation in different forest types may influence fuel load and consequently, fire behaviour. In rainforest there is an absence of understorey herbs, shrubs and monocots such as sedges and grasses that form an important fuel component in open sclerophyll forest (Howard, 1981; McArthur, 1967; Webb and Tracey, 1981b). Differences in the moisture content and chemistry of live fuels are also known to affect combustion (Pompe and Vines, 1966; King and Vines; 1969; Vines, 1981; Chandler *et al.,* 1983). Chemical influences include the effect of inorganic (mineral) constituents and the effect of organic substances (Vines, 1981). Organic compounds such as fats, oils and waxes facilitate ignition at relatively low temperatures (Pompe and Vines, 1966; Vines, 1981; Chandler *et al.,* 1983). Some plant species that dominate in open sclerophyll forest, such as *Eucalyptus,* contain large amounts of essential oils and they are normally found in the outer parts of plants, particularly in leaves (Chandler *et d.,* 1983). More study is required to assess potential differences in the flammability of leaves from rainforest and sclerophyll forest based on the effects of moisture content or the presence of inorganic and organic substances (Whelan, 1995).

The behaviour of fire is not only dependant upon the amount of fuel present, but also on the proportion of the fuel that is available to be burnt. The moisture content of the fuel has a direct and important influence on fuel availability and rate of spread (see Equation 1.1), and the intensity of fire increases exponentially with decreases in fuel moisture (Luke and McArthur, 1978; Cheney, 1981; Chandler *et d.,* 1983). Fine fuels in eucalypt forests become flammable when moisture content falls below about 20% (McArthur, 1967; Luke and McArthur, 1978; Cheney, 1981). Forest fuels absorb moisture from precipitation or directly from the atmosphere, losing moisture through evaporation. The rate of fuel drying after rain is a critical factor in determining potential flammability, most models predicting the behaviour of fire incorporate a drought index to express the increased availability of fuel as litter or grass dries (Cheney, 1981).

Empirical evidence related to drying of both dead grass and forest litter shows large amounts of moisture are lost quickly in the drying process, while a small amount persists permanently (Luke and McArthur, 1978). At moisture contents below 15%, the moisture content of fuel varies by absorption from and desorption into the atmosphere. In this state, moisture content will vary hourly and diurnally with the temperature and humidity of the air (McArthur, 1967; Luke and McArthur, 1978). McArthur (1967) determined the potential moisture contents of eucalypt fuels for a range of air temperatures and humidities, and included the measure in his fire danger meters. The drought index and moisture estimations developed by McArthur (1967) accurately predict moisture content in open eucalypt forests, but there is difficulty in applying them to rainforest because shading has an effect on moisture loss (McArthur, 1967; Luke and McArthur, 1978; Uhl and Kaufmann, 1990; Whelan, 1995). To determine differences in the flammability of rainforest and sclerophyll forest, it is necessary to quantify microclimatic differences between the two forest types, and relate this to fuel drying.

The other important parameters affecting fire spread are wind speed and topography; topography has an important direct effect as fire burns faster uphill and slower downhill (McArthur, 1967; Luke and McArthur, 1978; Cheney, 1981; Chandler *et al.*, 1983). The rate of forward spread of a fire increases exponentially with increases in wind speed and slope, the inverse is true when fire burns against the wind or downhill (McArthur, 1967). The importance of both wind speed and slope in promoting fire spread lies in their effects on radiation transfer and fuel preheating. Topography and wind direction determine the combined effect of the slope and wind speed during a fire. Topography and wind interact during intense fires and spotting is less likely to lead to fires on slopes in the lee of the prevailing wind (Luke and McArthur, 1978; Cheney, 1981, Chandler *et al.,* 1983).

Topography and the prevailing wind direction also interact to determine the moisture contents of fine fuels (Whelan, 1995). There is a complex interaction between the effects of topography, wind speed and rainforest which affects both rate of fire spread and the ignition potential (see Figure 1.1). Rainforest vegetation affects wind speeds and fuel drying (McArthur, 1967; Uhl and Kaufmann, 1990). The distribution of rainforest may, however, be largely governed by topography, there will thus be combined effects of the three variables which may protect certain positions from fire. This project allows examination of the factors involved in limiting fire spread in rainforest through examination of the effect of rainforest vegetation on fire. Figure 1.1 illustrates how vegetation may influence fire behaviour and the interaction between governing factors. It also provides an indication of the structure of this study. The specific objectives of the study are given in the following section.

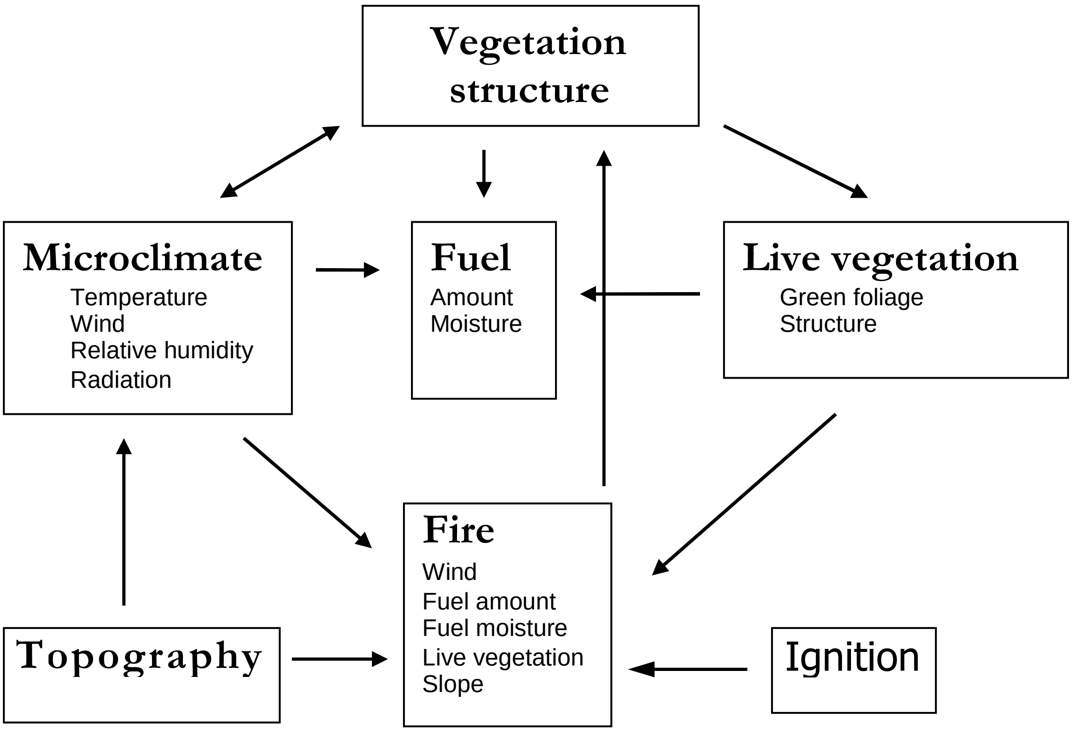


**Figure 1.1** Flow diagram illustrating the effect of vegetation on the factors governing bushfire behaviour.

## 1.4. Project Outline and Specific Objectives

In order to examine differences in the flammability of rainforest and sclerophyll forest, it was necessary to determine the effects of the vegetation on the key parameters of the general fire model (Figure 1.1). This meant examining the microclimates in both forest types and in the boundary vegetation between them, Section 2 details how this was done. The primary aim of analysing microclimatic differences was to be able to characterise conditions ie, the different environments in relation to fire behaviour. Specific objectives included being able to compare between the vegetation types, and to be able to predict conditions in the different forest types from conditions in the open. Both the information and the data from this analysis are required for determining the effects the different vegetation types have on fuel drying. Information regarding the effect of vegetation on wind speed is also necessary for inclusion in the general fire model.

Differences in fuel properties between rainforest and sclerophyll forest are examined in Section 3. The aims of this part of the study were to determine if the amount of fine fuel on the ground differed between the two forest types and to determine differences in fuel moisture content. Differences in fuel moisture content were examined by modelling fuel drying in the rainforest, the sclerophyll forest and the boundary between them from the microclimatic data collected. By modelling fuel drying after rain, it is possible to determine what is most important in preserving fuel moisture in the rainforest and to determine differences in flammability between the forest types. Information from this section forms an important input for the fire model.

A major part of this project was focused on differences in the structure or physical and chemical properties of live rainforest vegetation that may actively suppress fire. Section 4 describes an experiment that was conducted in order to assess differences in the flammability of individual leaves from the rainforest and sclerophyll forests. Individual leaves are an important focus because they are often the first parts of living plants which ignite during a fire (Gill and Moore, 1996). Section 5 analyses an experimental bushfire that was conducted to test if vines at high densities influence the forward progress of a fire in sclerophyll forest. It was considered important to test the specific effects of vines because they are a major component of many rainforest boundaries. Section 6 address questions about how differences in the structure of the understorey of rainforest and sclerophyll forest may affect fire rate of spread and where fires of different intensities are extinguished. In Section 7 the information from previous sections is combined to model how flammability in the different vegetation types differ, given the same weather conditions. Findings of the study are then discussed.

# Section 2. Microclimatic sampling.

## 2.1. Aims and Objectives

Measurement and characterisation of the microclimates in the rainforest, sclerophyll forest and boundary between them is fundamental to determining how each will influence fire behaviour. Differences in the microclimates of the different vegetation types may be related to canopy cover or topography. Reductions in wind speed, solar radiation and temperature under a closed canopy will lead to increases in relative humidity (McArthur, 1967; Uhl and Kaufmann, 1990; Whelan, 1995). Microclimatic conditions influence fire behaviour directly and indirectly, an important direct influence is the effect of wind speed. Temperature, relative humidity, solar radiation and wind speed have an important indirect effect on fire behaviour because together they determine fuel moisture content (Brutsaert, 1982; Pal Arya, 1988). Differences in canopy cover will thus affect the daily absorption and desorption of moisture by fine fuels and how this effects drying after rain (McArthur, 1967; Luke and McArthur, 1978; Chandler *et al.,* 1983).

The aim of this section of the project was to characterise differences in microclimatic conditions between rainforest, sclerophyll forest and the boundary. The important variables in terms of both direct and indirect effects on fire behaviour are solar radiation, air and surface temperature, humidity and wind speed. The specific aims were to collect microclimatic data to allow comparison and prediction of conditions between the different vegetation types, and if possible, to allow the prediction of conditions in the different vegetation types from conditions in the open. Other important aims of this section include gathering microclimatic data for determining the moisture contents of fine fuels in the different vegetation types (see Section 3) and determining differences in wind speed for direct use in the fire model (see Section 7).

## 2.2. Methods and materials

Microclimates in adjacent sclerophyll, boundary and rainforest vegetation were sampled using three meteorological towers connected to a single datalogger (Datataker, DT 500). In addition a single meteorological tower and datalogger at the Edith and Joy London Foundation in Kioloa provided a record of conditions in the open. Each tower was fitted with a sensor (Botany and Zoology, ANU.) for measuring photosynthetically active radiation (PAR); an anemometer (Vaisala, WAA15A), for recording wind run, and a temperature and relative humidity probe (Vaisala, HMP35A). The dataloggers were programmed to record values for each of these variables at five minute intervals; readings from the forest towers were taken simultaneously.
Records were taken from a range of sites but data from only two sites in the Kioloa Flora Preserve are included for analysis in this report. One of these sites had a southerly aspect and the other had a northerly aspect, both sites were sampled in summer and in winter, site descriptions and sampling dates of both forest sites and of the base station at Kioloa follow:

Southerly Aspect - This site was situated on a steep sandstone slope on the south side of a ridge with an elevation of 180 m a.s.l. (35°34'10"S, 150°19'50"E). Tall open sclerophyll forest dominates the upper slope which has a gradient of 5-15°, dominant species are *Eucalyptus pilularis* and *E. maculta* in the overstorey, and the monocot tussock *Lepidosperma urophorum* in the understorey. Below the first rocky outcrops downslope the gradient increases greatly and there was a narrow but distinct rainforest boundary zone, about 10 m wide. The rainforest extends down a slope of 20-30° to the valley floor. This site was sampled in summer from 15/12/96 to 12/1/97 and in winter from 17/6/97 to 21/8/97.

Northerly Aspect - This site was situated on a lower slope, approximately 100 m a.s.l. and with a gradient of about 10° (35°34'30"S, 150°19'20"E). Sclerophyll vegetation was dominant upslope and rainforest downslope. Part of this site was burned in mid 1996, this fire had extinguished naturally at the rainforest boundary. At this site the rainforest boundary was much wider, up to 50 m, the boundary zone is patchy with small rainforest trees and associated vines present in parts and *Eucalyptus* spp. and monocot tussocks present in adjacent areas. This site was sampled in summer from 12/1/97 to 17/3/97 and in winter 21/8/97 to 18/9/97.

Kioloa Base Station - This station was situated in a grazed pasture at the Edith and Joy London Foundation, about 4 km north of the forest sites. The position had an easterly aspect with an elevation of 10m a.s.l. and a slope of 5°, the site is approximately 500 meters from the ocean. This site was sampled from 15/12/96 to 21/8/97.

To determine the effects of season and weather on the microclimates in the different forest types, representative days from each site on each occasion were selected for analysis: two cloudy and two sunny days from both summer and winter were included. The data was examined in two ways: (1) Conditions in the different vegetation types and in the open were characterised by comparing observed values averaged for both summer and winter and both cloudy and sunny days; (2) Regression analysis was used to examine the relationship between the microclimates in the different locations in the short term. All analyses in this chapter are based on thirty minute running means of the five minute data. Running means were used because transient weather events such as clouds and wind gusts are not synchronous across all the sites. All comparisons and regression analyses reported in this chapter yield apparently significant relationships ($p<0.0001$), however, due to autocorrelation of the data these statistics give biased overestimates of the actual significance. Multiple sets of recording instruments were not available to replicate sites in time, and the statistical techniques required to cope with the spatial autocorrelation are not yet available. Aspect was included for analyses of this data but the aspect term is confounded by sampling date. This meant that while differences between the two aspects could be measured and factored out of analyses, the significance of the aspect effect is ignored

## 2.3. Results

Preliminary analysis of daily data revealed that there are location specific effects governing daily patterns of variance with certain parameters. Important location specific effects are illustrated by daily changes in PAR. Figure 2.1 shows that on a clear sunny day at Kioloa, changes in PAR between the vegetation types differ due to the effect of canopy gaps. This variation means that there are weak correlations in PAR between the different vegetation types, and when they are compared with Kioloa. Variation in the relationship between PAR in the open and at forest locations is also increased when there is partial cloud cover, due to the non-coincidence of cloud edges at the different locations. Further site specific effects occur due to differential delays in the response of microclimates in the different locations to external conditions. This effect is illustrated in Figure 2.2 for relative humidity: there are different delays in the response of relative humidity in each location. Because there are differential lags in response, correlations between the different locations exhibit strong hysteresis.

Comparison of microclimatic means between the different vegetation types and conditions in the open shows that there are clear differences between them. Figure 2.3 shows that differences in the microclimates at each location remain similar between summer and winter and between cloudy and sunny days. Comparison of mean relative humidity shows that rainforest is most humid, and that relative humidity is higher at forest sites than in the open. There are greater seasonal differences in relative humidity in the rainforest than in the other vegetation types but cloudiness does not affect humidity in the rainforest as much.

Comparison of mean daily temperatures for summer and winter shows that there is little difference between vegetation types. Rainforest is cooler than sclerophyll forest or the open, but the boundary is cooler than the rainforest in winter. The open site at Kioloa stays warmer than the forest in winter. Cloudiness has a stronger effect on the relationship between the different locations: temperatures on cloudy days are above those of clear days because night time temperatures are increased by cloud cover. The Kioloa site is most affected by cloudiness, the rainforest is least affected. Kioloa is the warmest site on cloudy days and the coolest site on sunny days (largely due to sea breezes), rainforest is warmer than the other locations on sunny days because it does not get as cold at night.

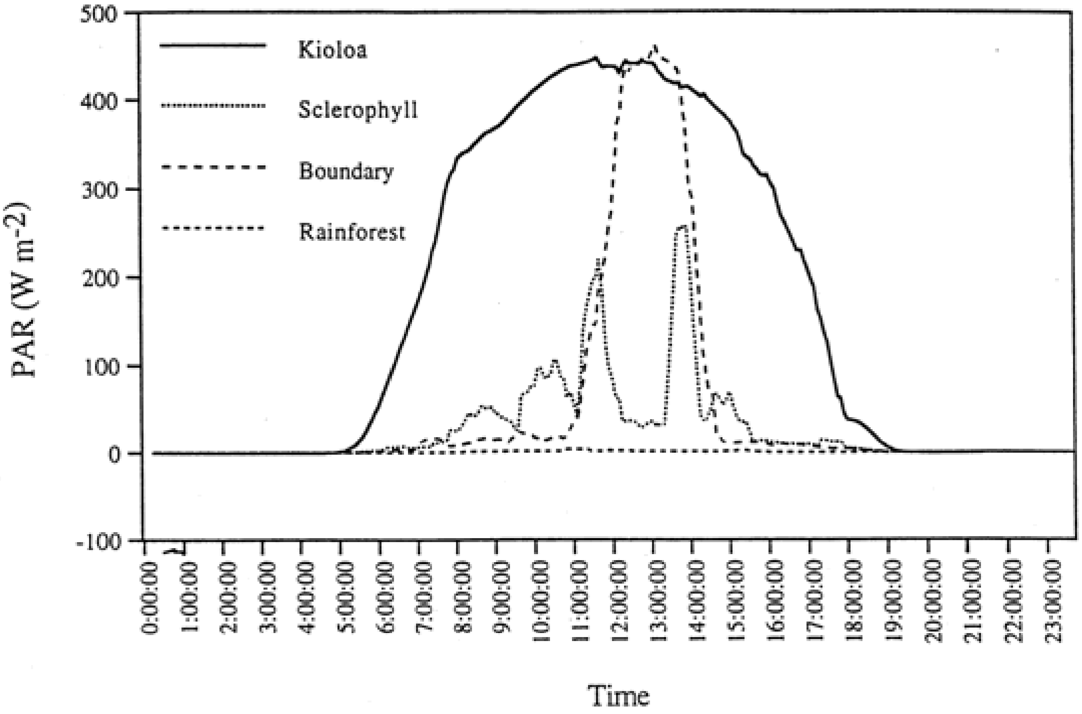


**Figure 2.1** Thirty minute running means of PAR on 31/1/97

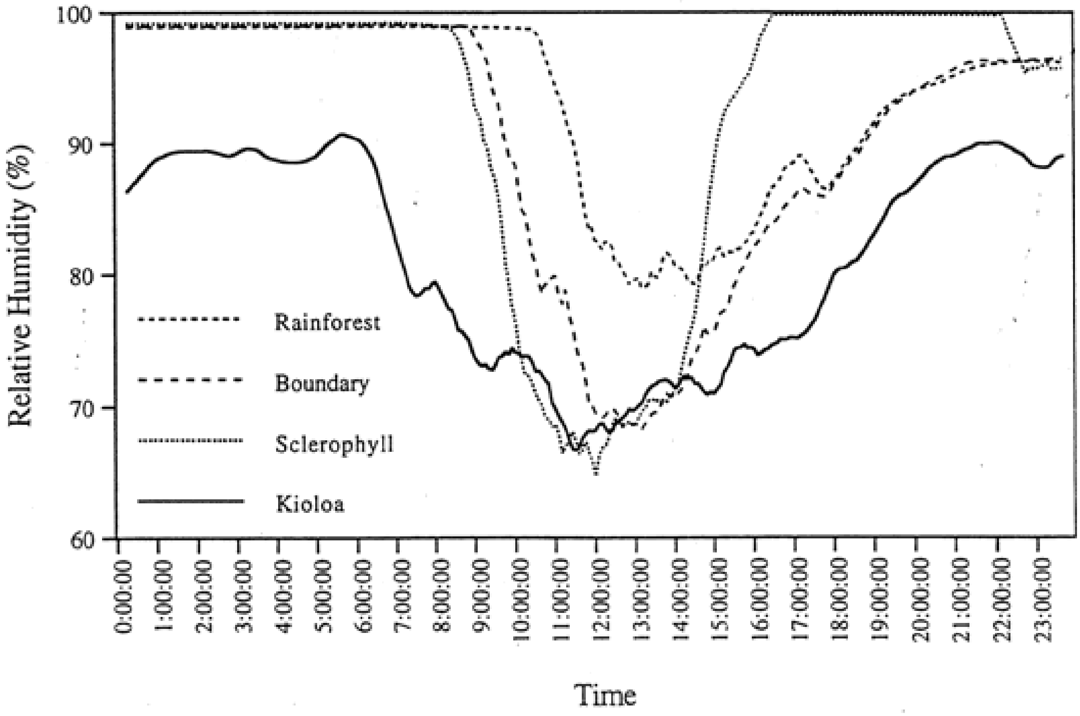


**Figure 2.2** Thirty minute running means of relative humidity, 31/1/97

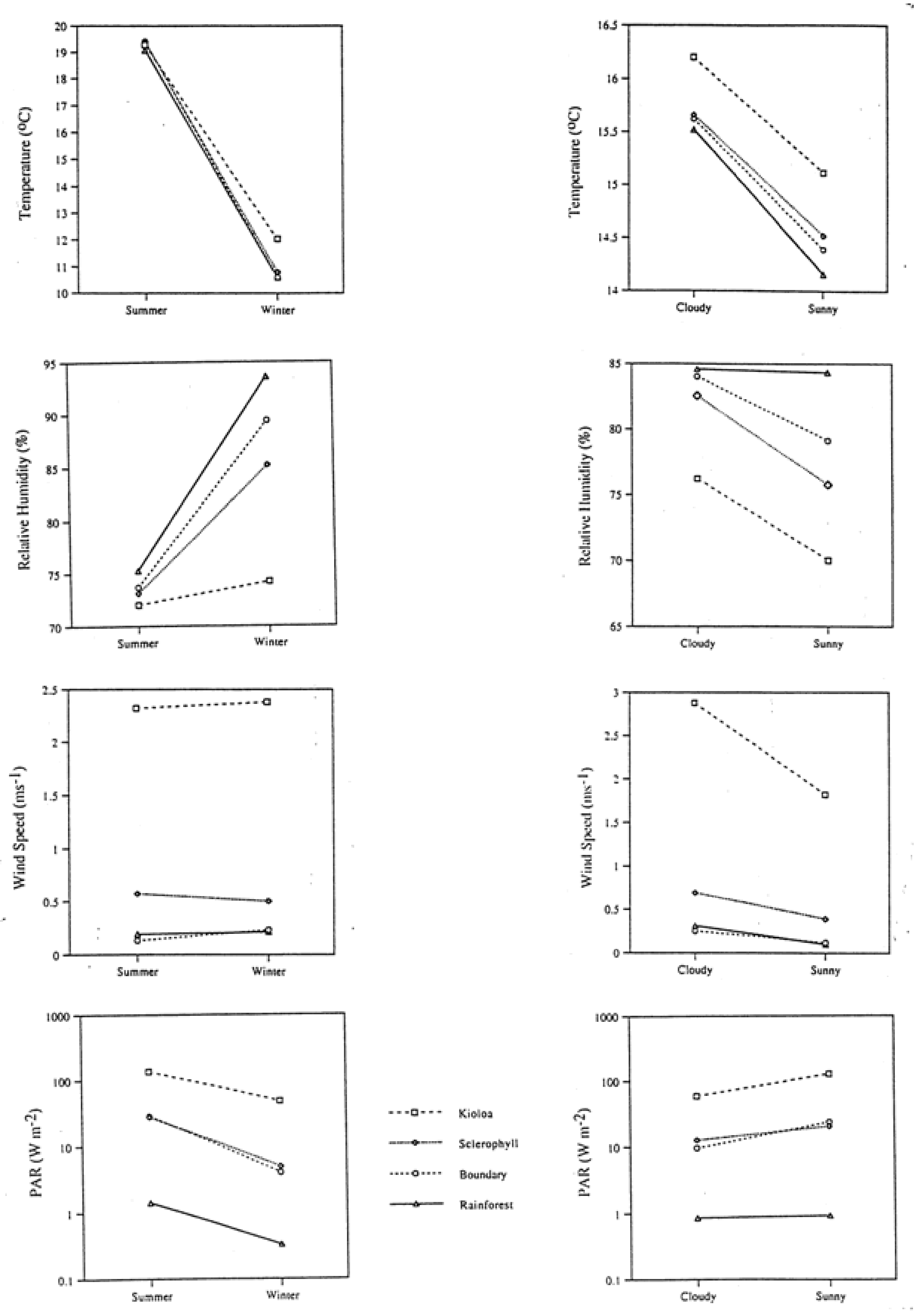


**Figure 2.3** Comparison of microclimatic means by season (left) and weather (right).

Comparisons of mean PAR are as expected: far less light penetrates the rainforest canopy than the sclerophyll or boundary canopies and light is reduced in all vegetation types from levels in the open. PAR levels are affected by both season and cloudiness, but this does not appear to affect the relationship between the sites. Results for the boundary are not obviously different to those for the sclerophyll forest. Comparisons of mean wind speed by season and weather show that Kioloa is far windier than the other sites due its proximity to the ocean and open pasture. Kioloa experienced relatively higher wind speeds on cloudy days. Rainforest and rainforest boundaries are less windy than sclerophyll forest. Season has little effect on mean daily wind speeds, even at Kioloa.

The results of regression analysis for all the forest types compared with conditions in the open are shown for each parameter in Tables 2.1 to 2.4. Figure 2.4 shows plots of climate values for the rainforest compared with those of Kioloa and the sclerophyll forest. Again, relationships between the different vegetation types vary with the parameter. There is an obvious lack of fit (low $R^2$ value) in some models, but results show that rainforest is consistently darker, cooler, more humid and less windy than the other vegetation types. There are moderate to strong correlations between conditions in the rainforest, the boundary and the sclerophyll forest but it was difficult to predict forest conditions from conditions at Kioloa. Specific results for each parameter are described below.

Table 2.1 shows relationships between relative humidities in the different locations. When the forest sites are compared to Kioloa, regression slopes are greater than 1.0 for the rainforest and sclerophyll forest, which means that relative humidity in these vegetation types increases faster than in the open. The regression slope for the boundary is about 1.0 but the intercept is high so it remains more humid in the boundary than in the open. Correlations between the forest sites and Kioloa are poor (see Table 2.1 and Figure 2.4) which means that short term values at forest sites cannot be accurately predicted from the open, this is due to the effects of daily hysteresis in the data and longer term differences in drying following rain. Regression analyses between the different vegetation types yields strong relationships ($R^2$ values c. 0.95).

Results from regression analysis of temperature are shown in Table 2.2: $R^2$ values for temperature are high between forest sites, and when the sites are regressed against Kioloa. Temperatures in all vegetation types are cooler than Kioloa. All slopes are greater than one; this means that it gets hotter faster at forest sites than at Kioloa. This is probably because the sea breeze limits temperature at Kioloa, it can be seen from Figure 2.4 that the relationship between temperature in the open and in the forest appears to be non-linear. Comparison between the vegetation types shows that temperatures in both the sclerophyll forest and rainforest boundary change more than in the rainforest.

The $R^2$ values for regression analysis of PAR are very low ($R^2$ values c. 0.20), this is due to site specific canopy and weather effects. Figure 2.4 shows the effect canopy gaps have on correlations. Despite the poor fit it can be seen that, as would be expected, all forest sites are darker than the open, rainforest is the darkest. The boundary receives more light than the sclerophyll forest but that values change more in the sclerophyll forest. This may be because of the patchy nature of the boundary.

Results from the regression analysis of wind speeds (Table 2.4 and Figure 2.4) show that relationships between the forest sites and Kioloa are weak ($R^2$ values c.0.30) and there are only moderate correlations ($R^2$ values c.0.60 to 0.80) between the different vegetation types. This is due to the non-coincidence of gusts and fluctuations in wind direction. The effects of these factors are clearly shown in Figure 2.4. Despite the low $R^2$, trends in the relationships still emerge, Kioloa was far windier than any of the forest sites, rainforest and rainforest boundaries are less windy than sclerophyll forest.

**Table 2.1** Regression analyses predicting relative humidity (%) between forest types and open pasture (Kioloa)

| | | Intercept | | Slope | | | |
|---|---|---|---|---|---|---|---|
| **Response** | **Predictor** | **Est.** | **s.e.** | **Est.** | **s.e.** | **F-ratio** | **$R^2$** |
| Sclerophyll | Kioloa | 1.48 | 0.98 | 1.06 | 0.01 | 6480 | 0.59 |
| Boundary | Kioloa | 7.35 | 1.06 | 1.01 | 0.01 | 4994 | 0.54 |
| Rainforest | Kioloa | -0.24 | 1.22 | 1.09 | 0.02 | 4442 | 0.57 |
| Rainforest | Sclerophyll | 11.20 | 0.29 | 0.89 | 0.00 | 58206 | 0.94 |
| Boundary | Sclerophyll | 5.07 | 0.23 | 0.96 | 0.00 | 119775 | 0.96 |
| Rainforest | Boundary | 6.97 | 0.19 | 0.93 | 0.00 | 161035 | 0.98 |

**Table 2.2** Regression analyses predicting temperature (°C) between forest types and open pasture (Kioloa)

| | | Intercept | | Slope | | | |
|---|---|---|---|---|---|---|---|
| **Response** | **Predictor** | **Est.** | **s.e.** | **Est.** | **s.e.** | **F-ratio** | **$R^2$** |
| Sclerophyll | Kioloa | -1.88 | 0.11 | 1.08 | 0.01 | 24533 | 0.84 |
| Boundary | Kioloa | -2.33 | 0.11 | 1.11 | 0.01 | 26206 | 0.85 |
| Rainforest | Kioloa | -1.44 | 0.11 | 1.04 | 0.01 | 23681 | 0.84 |
| Rainforest | Sclerophyll | 0.50 | 0.04 | 0.95 | 0.00 | 174307 | 0.97 |
| Boundary | Sclerophyll | -0.24 | 0.03 | 1.01 | 0.00 | 385325 | 0.98 |
| Rainforest | Boundary | 0.70 | 0.02 | 0.94 | 0.00 | 530732 | 0.99 |

**Table 2.3** Regression analysis predicting PAR (W m$^{-2}$) between forest types and open pasture (Kioloa)

| | | Intercept | | Slope | | | |
|---|---|---|---|---|---|---|---|
| **Response** | **Predictor** | **Est.** | **s.e.** | **Est.** | **s.e.** | **F-ratio** | **R$^2$** |
| Sclerophyll | Kioloa | -0.43 | 0.42 | 0.18 | 0.00 | 4068 | 0.47 |
| Boundary | Kioloa | -2.16 | 0.78 | 0.20 | 0.01 | 1483 | 0.25 |
| Rainforest | Kioloa | 0.12 | 0.04 | 0.01 | 0.00 | 1104 | 0.20 |
| Rainforest | Sclerophyll | 0.39 | 0.03 | 0.03 | 0.00 | 792 | 0.15 |
| Boundary | Sclerophyll | 4.52 | 0.74 | 0.69 | 0.02 | 1112 | 0:20 |
| Rainforest | Boundary | 0.61 | 0.03 | 0.01 | 0.00 | 332 | 0.07 |

**Table 2.4** Regression analysis predicting PAR (m s$^{-1}$) between forest types and open pasture (Kioloa)

| | | Intercept | | Slope | | | |
|---|---|---|---|---|---|---|---|
| **Response** | **Predictor** | **Est.** | **s.e.** | **Est.** | **s.e.** | **F-ratio** | **R$^2$** |
| Sclerophyll | Kioloa | 0.09 | 0.01 | 0.19 | 0.00 | 2004 | 0.30 |
| Boundary | Kioloa | -0.06 | 0.01 | 0.10 | 0.00 | 1956 | 0.30 |
| Rainforest | Kioloa | -0.01 | 0.01 | 0.09 | 0.00 | 1564 | 0.26 |
| Rainforest | Sclerophyll | -0.03 | 0.00 | 0.44 | 0.00 | 11585 | 0.72 |
| Boundary | Sclerophyll | -0.04 | 0.00 | 0.42 | 0.01 | 6169 | 0.58 |
| Rainforest | Boundary | 0.05 | 0.00 | 0.82 | 0.01 | 14881 | 0.77 |

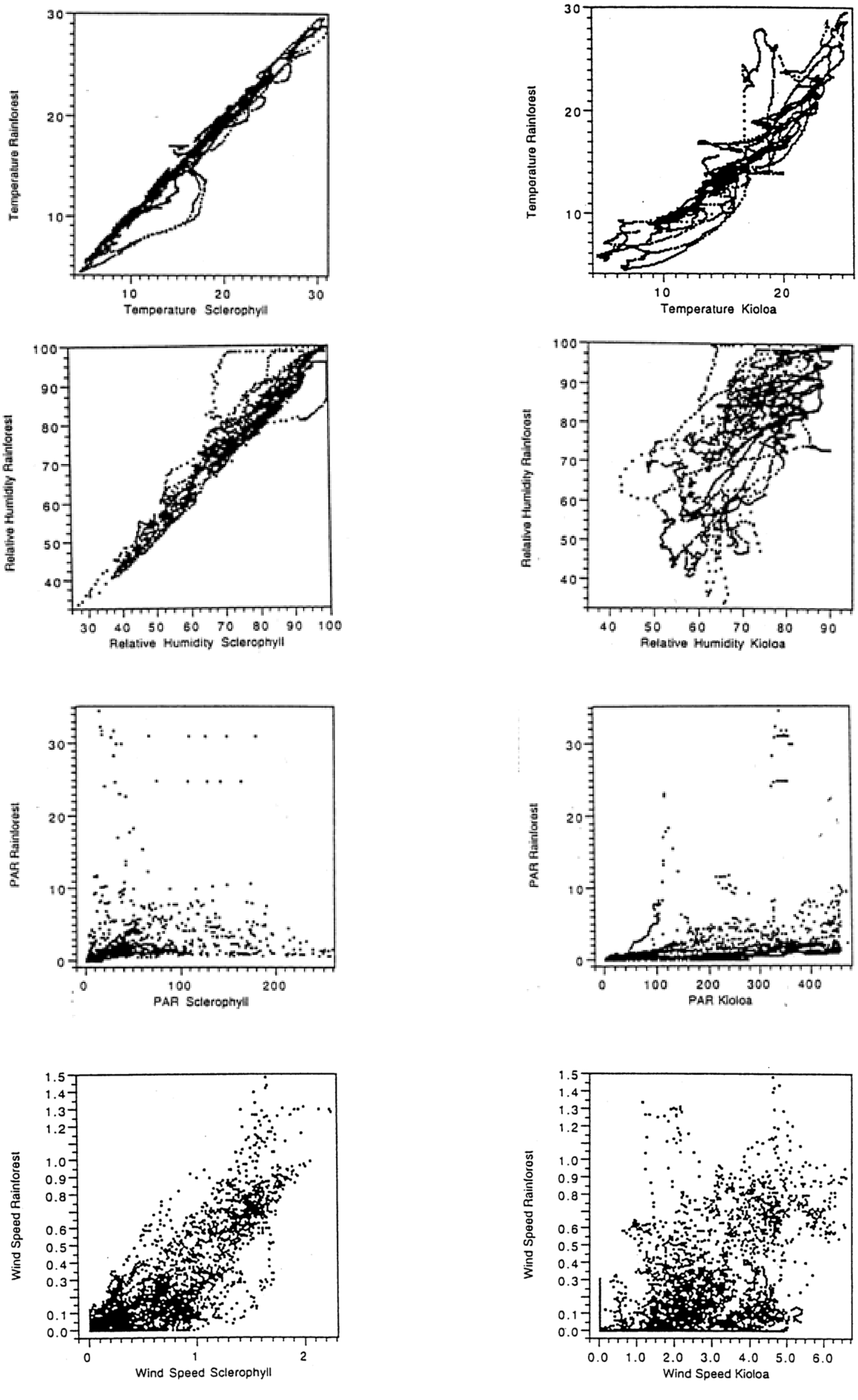


**Figure 2.4** Comparisons of rainforest temperatures (°C), relative humidities (%), PAR (W m$^{-2}$) and wind speed (m s$^{-1}$) with those in the sclerophyll forest (left) and the open (right)

## 2.4. Discussion

There are obvious seasonal effects on the parameters linked to solar radiation. Light and temperature are both high in summer and low in winter while relative humidity follows the reverse trend. There are also effects linked to cloudiness; as expected, there is less light and higher humidity on cloudy days. Mean daily temperatures are increased in all locations on cloudy days because cloud cover restricts cooling during the night. Rainforest is consistently darker, cooler, more humid and less windy than sclerophyll forest, and all forest sites are darker, more humid and less windy than the open. There is an interaction between the effects of location and the effects of season and cloudiness; rainforest temperature is relatively unaffected by differences between cloudy and sunny days because a dense canopy cover retains heat even on cloudless nights. This canopy effect also means that relative humidity in the rainforest is relatively unaffected by cloud cover. It is concluded that in relation to these effects, rainforest is more buffered from extremes in weather than the boundary, the sclerophyll forest or the open. Relative humidity varies more in the rainforest than at other locations but rainforest remains more humid, especially in winter. The boundary was variable: in relation to solar radiation and temperature the rainforest boundary is similar to the sclerophyll forest, but boundary wind speeds are more similar to the rainforest. These results highlight the patchy nature of boundary vegetation which may be more like rainforest in certain parts, sclerophyllous in other areas and distinct elsewhere.

The results of the regression analysis show that it is possible to define the relationships between microclimates in the different locations with varying degrees of certainty. These results support the results from the comparison of daily means showing that rainforest is darker, cooler during the day, more humid and less windy than the boundary and the sclerophyll forest and that it is darker, more humid and less windy in all forest types than it is in the open. Regression also showed that the rainforest is more buffered from extremes in weather conditions and that conditions in the boundary may vary between being similar to the rainforest and similar to the sclerophyll forest.

The results show that it is possible to characterise and define the relationships in the parameters between the forest types but that there may be issues of scale that confound the predictive power of comparison. It has been shown that at the daily level (Figure 2.3) trends in the response of parameters are quite clear while in the short term (Figure 2.4) relationships may be confounded by the effects of canopy cover, non-coincidence of external weather and daily hysteresis. These effects mean that it is not possible to accurately predict forest conditions for all microclimatic variables from current conditions in the open. To overcome the problems of time lags in predicting variables such as relative humidity, litter or moisture content, it is necessary to either fit models with time lags or to simulate changes over time. The latter approach is used in the next chapter. Despite problems in the scale of prediction these results show that rainforest is more buffered from changes in external conditions than sclerophyll, and that the rainforest microclimate is such that fuel will dry slower here than in the sclerophyll forest. This factor, and the fact that wind speeds are reduced in the rainforest from those of sclerophyll forest, means that rainforest will remain less flammable than sclerophyll forest. The results show that conditions at the rainforest boundary may be variable; this is due to the patchy nature of boundary vegetation and means that differences in the flammability of the boundary and the sclerophyll forest will vary on a site specific basis.

# Section 3. Dead fuel loads and their moisture contents.

## 3.1. Aims and Objectives

This chapter is focused on determining if there are consistent and predictable differences in the moisture contents of fine dead fuels in the rainforest, the boundary zone and the sclerophyll forest. The primary aim of this section was to model fuel drying in the different vegetation types, hence field sampling was undertaken to measure both the moisture content of the fine fuels and the amount of fine fuel in each vegetation type. Fine material such as leaf litter, bark and twigs up to 6 mm in diameter is the most important fuel for forest fires. This is because larger fuels will not ignite unless fine fuels are present and it is fine fuels that contribute most to the flaming phase of combustion (Luke and McArthur, 1978). Below the moisture content level described by Cheney (1981), the rate of forward spread of a fire increases exponentially with decreases in fuel moisture (McArthur, 1967; Luke and McArthur, 1978; Cheney, 1981; Chandler *et al.,* 1983). Fine forest fuels may be saturated by rain or dew, they then dry by evaporation. The effect of vegetation on microclimate and shading, influences both evaporation after rain and daily adsorption and desorption of moisture by fuels (McArthur, 1967; Luke and McArthur, 1978). The effects of vegetation type on fuel drying after rain is an important determinate of how fire will behave in that vegetation type.

An evaporation model was used to examine the effects of vegetation type on the daily adsorption and desorption of moisture by fine fuels and how this affects fuel drying after rain. The model was developed to predict evaporation based on the five minute microclimatic data (Chapter 2). The model used is based on the Penman equation for evaporation from an exposed wet surface (Brutsaert, 1982; Pal Arya, 1988), the Penman equation is given below (Equation 3.1). This equation calculates evaporation from the difference between the saturation vapour pressure at the evaporative surface and the actual vapour pressure of the air immediately above it. The first term is a function of air temperature and solar radiation, the second is dependant on relative humidity and wind velocity (Brutsaert, 1982; Pal Arya, 1988). The Penman equation had to be modified to model evaporation over time from forest fuels (the modified equation is given in Appendix 1).

An important aim of field sampling was to collect samples from the sites where the microclimatic records were collected for calibration of the evaporation model. Field samples also show if there are consistent differences in mean moisture contents and the rate fuels dry in the rainforest, rainforest boundary and sclerophyll forest over a range of sites. Field sampling also enabled measurement of fuel loads at the same time as moisture contents.

$$E_p = Q\left(\frac{\Delta}{\Delta = \gamma}\right) + E_a\left(\frac{\gamma}{\gamma + \Delta}\right)$$

Where,

$E_p$ = Potential evaporation

$Q$ = Net radiation, adjusted for a forest canopy

$\Delta$ = Gradient operator, dependent on saturation vapour pressure and temperature.

$\gamma$ = Psychrometer constant.

$E_a$ = Drying power of air, dependent on wind speed and rel. humidity

**Equation 3.1** The Penman equation for evaporation from an exposed wet surface (Brutsaert, 1982; Pal Ary a, 1988)

## 3.2. Methods and materials

Field sampling of leaf litter in the different vegetation types was undertaken between January and May. During this period, sampling was undertaken on seven different occasions; early sampling was conducted during summer when fuel moisture contents were low and fire danger was high. On each occasion 10 samples were taken, from where the meteorological towers were situated at the time for calibration of the evaporation model. Litter sampling was undertaken while the meteorological equipment was at two different sites, site descriptions are given below. At Site 1 leaf litter samples were taken in both the burnt sclerophyll areas and an adjacent unburnt area of sclerophyll forest.

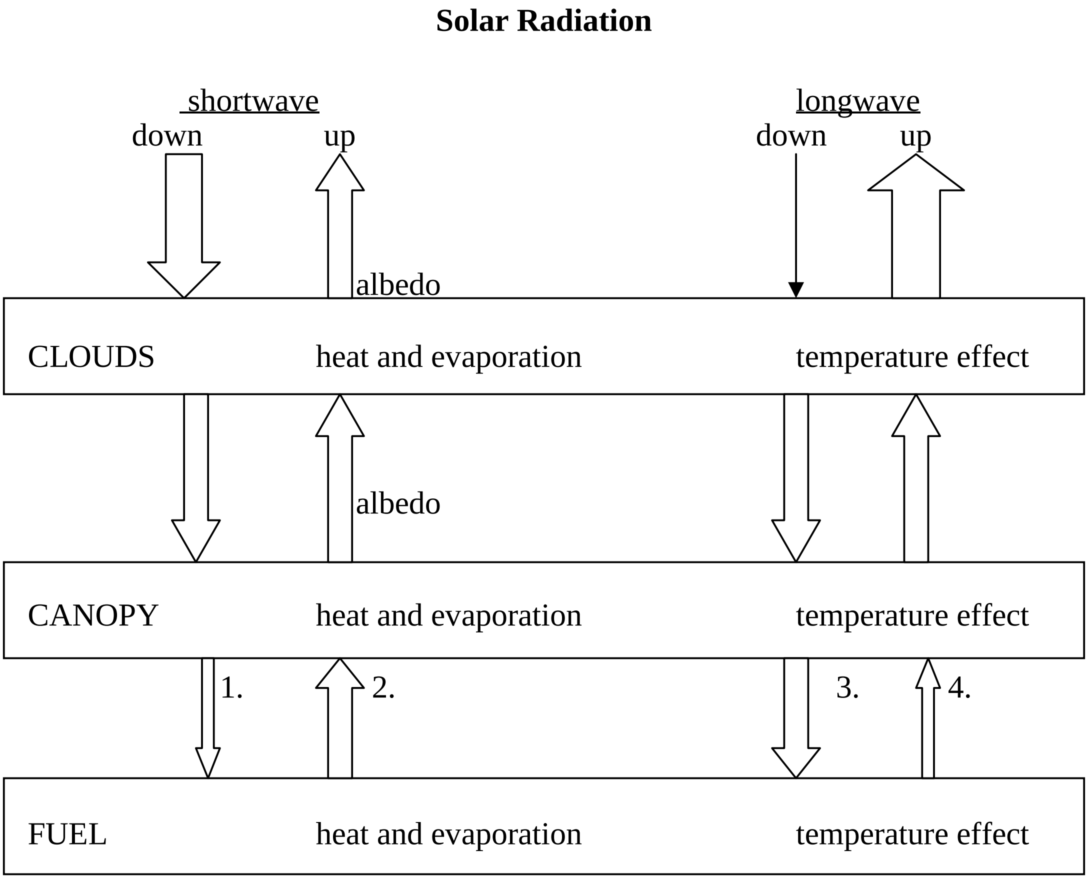
Site 1 - See northerly aspect in Chapter 2. Litter sampling was undertaken while the tower was at this site between 12/1/97 and 17/3/97.

Site 2 - This site was on the south side of a large rainforest patch (35°34'40"S, 150°19'20"E) in a low topographic position (70 m a.s.l.) with little to no slope at the rainforest boundary. The boundary here was patchy and varied in width but was little more than ten meters wide in most places. The meteorological equipment was at this site during autumn from 17/3/97 to 2/5/97.

On all but one occasion, samples were taken at two or more sites. Eight different sites were sampled, these included both north and south facing slopes around five different rainforest valleys. Sampling was conducted at ten meter intervals along transects in the sclerophyll forest, the rainforest boundary and the rainforest. Five samples were taken from each transect at all sites except where towers were situated. All the litter that fell within a 400 $cm^2$ quadrat was collected. Samples were placed in plastic bags to minimise moisture loss. Each sample was weighed wet, then oven dried and weighed again to allow calculation of moisture contents as a ratio of wet weight over dry weight. The moisture ratio was analysed by ANOVA, including vegetation type, time since rain, aspect, site, and valley as predictive variables. Regression analyses were also used to compare means for each vegetation type over the range of sites and occasions.

To model evaporation over time from forest fuels, the Penman equation had to be modified (see Appendix 1). Firstly, it was necessary to incorporate a term that accounted for the presence of a canopy above the evaporative surface. This was done by using an equation based on the effect of a patchy fog cover on evaporation (Brutsaert, 1982) which has infra-red emission properties similar to a canopy cover. This term was calibrated to forest conditions by measuring the effects of canopy on incoming and outgoing solar radiation (Figure 3.1). The effects of canopy cover on incoming shortwave radiation and the effect of litter on outgoing shortwave radiation (albedo) were measured. The effect of the canopy on incoming longwave radiation was estimated from canopy density and temperature. The effect of litter on outgoing longwave radiation was calculated from surface temperature. The inclusion of this term in the model meant that a canopy cover estimate had to be optimised for each of the three vegetation types (see Appendix 1).

Past work has shown that moisture loss by forest fuels is roughly proportional to the remaining water content (Luke and McArthur, 1978), therefore moisture loss was made proportional to residual moisture. A drying constant, defining the specific proportional relationship of the curve, had to be optimised over a number of different drying periods. The drying constant and canopy cover estimate term were optimised by calibrating the model against litter samples collected at the sites, evaporation was modeled over five periods after rain. Evaporation from each different vegetation type was modeled separately. When the accuracy of the predictive model had been established it was used to estimate fuel moisture loss in the different vegetation types during both summer and autumn. Moisture loss was modeled for periods of 28 days after rain. By comparing drying curves it is possible to determine differences in the time it takes for fuels in each vegetation type to reach moisture levels where fuel becomes flammable.



Where
1. Measured
2. Measured
3. Estimated from 1,. canopy density and estimated canopy temperature
4. Calculated from temperature

**Figure 3.1** Field calibration of canopy cover term

## 3.3. Results

Results of the ANOVA comparing the moisture contents of field samples in terms of the influence of time since rain; valley, aspect and vegetation type are shown in Table 3.1. The best model that could be generated used these variables to predict $Log_{10}$ of moisture content, this model showed that transect and sampling occasion were very significant for predicting fuel moisture, valley was less significant and aspect was insignificant. The mean moisture contents and standard errors for each vegetation type as given by this model are as follows: rainforest 72% (±3%); boundary 55% (±3%); sclerophyll 51% (±3%); and the burnt site 36% (±5%). There is little difference between the boundary and the sclerophyll forest, while rainforest is much moister. Moisture contents in the burned sclerophyll forest were well below those of unburned sclerophyll forest.

**Table 3.1** Influence of time since rain, vegetation type and site factor on $\mathrm{Log}_{10}$ fuel moisture ratio

**$R^2$ = 0.72, F-ratio = 91.99**

| **Term** | **F-ratio** | **Prob>F** |
|---|---|---|
| Time since rain | 184.46 | 0.0000 |
| Valley | 3.06 | 0.0165 |
| Vegetation Type | 33.35 | 0.0000 |
| Aspect | 0.32 | 0.5697 |

Results from the regression analysis of the means for each vegetation type from each site on each occasion are shown in Table 3.2. In all cases values from unburned sclerophyll forest were used to predict moisture content in the other vegetation types. This analysis shows that there are strong linear correlations between fuel moisture contents in the different vegetation types. The slope of the lines represents the drying relationship between fuels in the different vegetation types because samples were taken at different times after rain. It can be seen that small changes in the moisture content of sclerophyll fuels are matched by larger changes in the moisture content of rainforest and boundary fuels, and rainforest maintains a higher moisture content. Fuels in unburned sclerophyll forest change moisture contents faster than, and remain wetter than fuels in burnt sclerophyll forest.

**Table 3.2** Results of regression analyses predicting moisture contents in rainforest, boundary and burnt sclerophyll from the sclerophyll forest

| | | **Intercept** | | **Slope** | | | | |
|---|---|---|---|---|---|---|---|---|
| **Response** | **N** | **Est.** | **s.e.** | **Est.** | **s.e.** | **$R^2$** | **F-ratio** | **Prob>F** |
| Rainforest | 24 | -0.09 | 0.17 | 1.20 | 0.11 | 0.84 | 119.20 | 0.00 |
| Boundary | 24 | -0.13 | 0.16 | 1.11 | 0.10 | 0.83 | 111.87 | 0.00 |
| Burnt Scler. | 6 | 0.52 | 0.26 | 0.57 | 0.16 | 0.74 | 11.43 | 0.03 |

The field samples were also used to examine if there are consistent differences in the quantity of fine fuels (fuel load) on the ground in each vegetation type. An ANOVA was conducted on the dry weights of all samples using site and vegetation type as the predictive variables (Table 3.3). This model explained little variation, but both vegetation type and site were significant terms. The mean fuel load kg $m^{-2}$ (and standard errors) for each vegetation type are as follows: rainforest 0.65 (±0.02); boundary 0.81 (±0.03); sclerophyll forest 0.78 (±0.04); and the burnt sclerophyll forest 0.76 (±0.06). The boundary, sclerophyll forest and burned sclerophyll site are similar in fuel loads but rainforest has slightly less fuel.

**Table 3.3** Influence of site and vegetation type on dry weight of litter samples

**$R^2$ = 0.09, F-ratio = 5.06**

| **Term** | **F-ratio** | **Prob>F** |
|---|---|---|
| Site | 4.88 | 0.0001 |
| VegetationType | 5.36 | 0.0012 |

Litter sampling yielded five different drying periods for calibration of the litter moisture model, Table 3.4. Cloud cover had to be estimated for each period. Drying was modeled separately for each vegetation type, which gave a total of 15 curves for calibration. Analysis was based on a hypothetical fuel loading of 1 kg $m^{-2}$. The maximum water a fuel can hold and litter water at the start of each drying period was standardised at 1.5 kg $m^{-2}$. The canopy cover estimates for each vegetation type were optimised at 98% for the rainforest, 93% for the boundary and 87% for the sclerophyll vegetation. The drying constant was optimised at 0.3, the results of this calibration are show in Figure 3.2. This figure shows the moisture contents and 95% C.I. for the field samples at the end of each drying period compared with results from the litter moisture model. Eight estimates fell within the 95% C.I. for the field samples, 7 curves were outside, but of these three were only just outside the interval.

**Table 3.4** Drying periods for calibration of the litter moisture model, all dates in 1997

| **Drying Period** | **Cloud Cover** (%) | **Date From** | **Date To** |
|---|---|---|---|
| 1 | 15 | 9th January | 22nd January |
| 2 | 20 | 2nd February | 6th February |
| 3 | 20 | 7th March | 17th March |
| 4 | 50 | 23rd March | 27th March |
| 5 | 15 | 7th April | 22nd April |

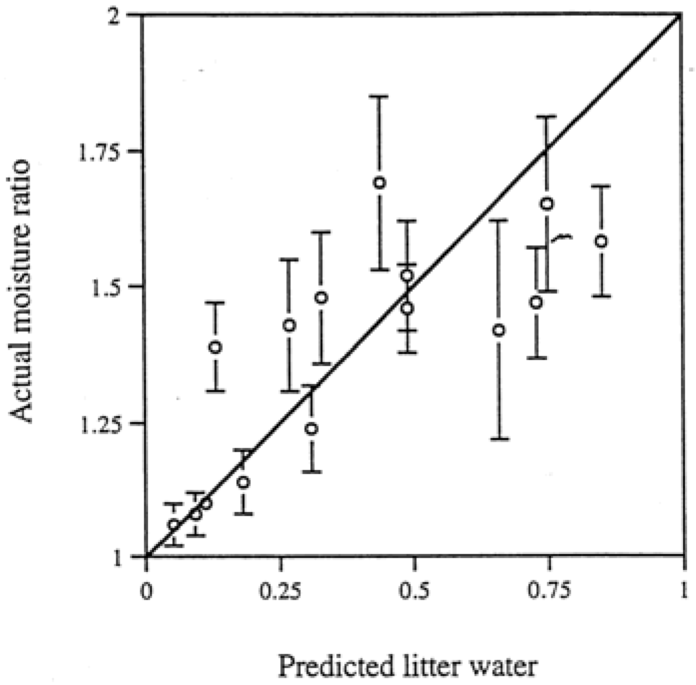
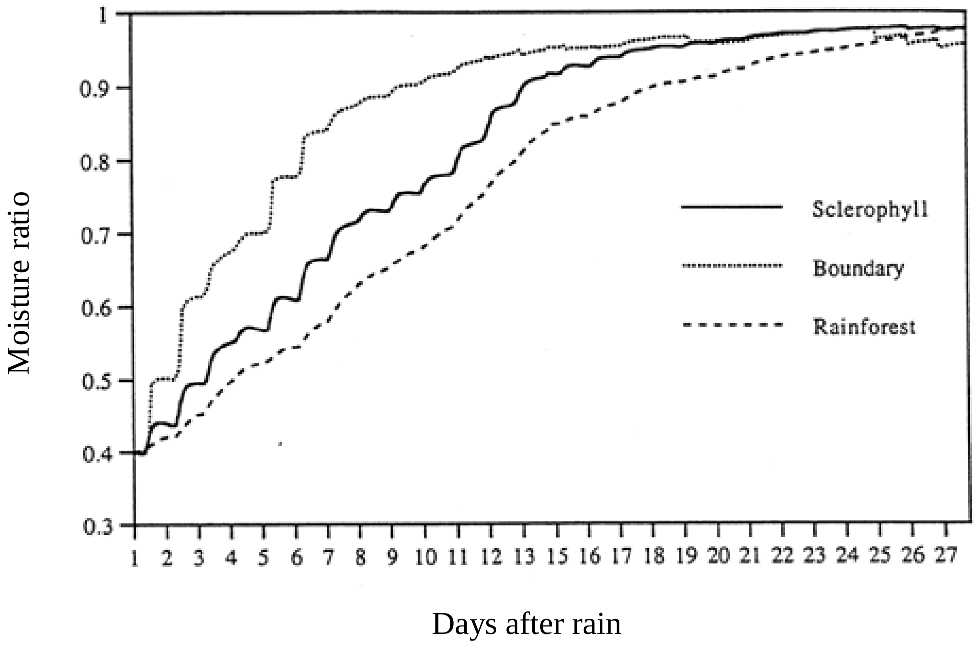


**Figure 3.2** Results of litter moisture model predictions against observed values and 95% C.I.

After calibration, the model could be used to indicate trends in fuel moisture in the. different vegetation types after rain. Fuel drying in each vegetation types from an initial moisture ratio of 1.5 to the dry weight, estimated for periods during both summer and autumn is shown in Figure 3.3. The curves demonstrate that there are differences in the daily absorption and desorption of moisture by fuels in each of the vegetation types. Fine fuel in the sclerophyll forest and the boundary is shown to loose moisture faster than rainforest fuels but fuels in the more open vegetation types also absorb more moisture during cool cloudless nights. There are differences in the number of days it takes fuel in each vegetation type to reach a moisture content of 20% (moisture ratio = 0.80) at which they will become flammable. In summer, rainforest fuels took 14 days to become flammable, while sclerophyll fuels took 12 days, fuel in the boundary dried quicker than even the sclerophyll fuels. The results for Autumn show that litter in the sclerophyll forest and the rainforest boundary will become flammable 23 to 26 days after rain while the rainforest is not flammable even after 28 days without rain.

Summer



Autumn

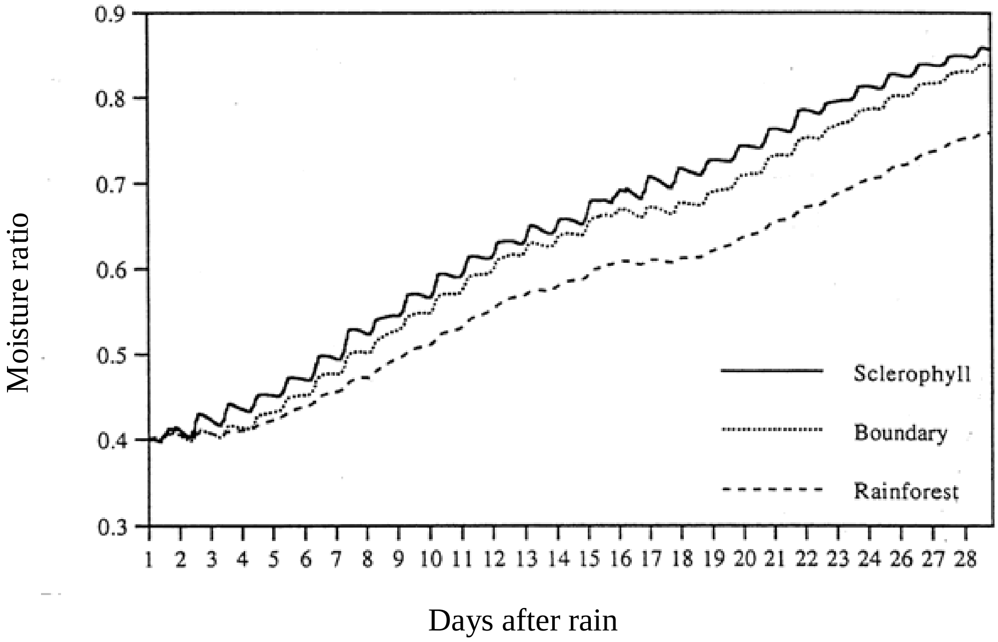


**Figure 3.3** Drying curves for litter (expressed as a moisture ratio of wet wt./dry wt.) in the rainforest, the rainforest boundary and the sclerophyll forest for both summer and autumn.

## 3.4. Discussion

The results from field sampling show that vegetation type affects the dryness of fine dead fuels. Sclerophyll fuels are usually drier than boundary fuels, which are usually drier than rainforest fuels. There was some suggestion from field data that rainforest fuels have a higher moisture content immediately after rain than fuel in the sclerophyll forest. This is possible because the fibre saturation point of the fuels may vary (Whelan, 1995). Results from the analysis of fuel loads show that there is slightly less fine dead fuel on the ground in the rainforest than there is in the sclerophyll forest. This is probably due to differences in rates of decomposition or litter production between rainforest and sclerophyll forest (Howard, 1981; Mullen, 1995; Adam, 1994). Field sampling has shown that there are differences in flammability of the litter in rainforest and sclerophyll forest based on the moisture contents of fine dead fuels, but there is little difference of the amount of fine dead fuel on the ground. At the rainforest boundary the moisture contents and amount of fine dead fuels are very similar to those of the sclerophyll forest.

Calibration of the litter moisture model showed that it is possible to predict evaporation from leaf litter based on five minute microclimatic data. Some error in predicted litter moisture had to be accepted because the model is optimised over several variables. There are a number of factors that may have complicated prediction in certain cases. Optimisation of the canopy cover means that certain natural factors can not be incorporated, two different sites were used for calibration: canopy cover would have differed between them. The estimate would also vary with the position of the sun at the time. Initial moisture contents may vary, depending upon the amount of rainfall. Potential shielding effects by the canopy, and cloud cover is difficult to estimate accurately. There may also be complications arising from the fact that meteorological data was collected at points whereas litter samples were collected along transects. Despite issues concerning calibration it can be concluded that the model can give a reasonably accurate prediction of moisture loss from leaf litter after rain.

Analyses of drying curves for leaf litter from the rainforest, the rainforest boundary and the sclerophyll forest for extended periods in summer and autumn, shows that there are differences in the daily absorption and desorption of moisture by fuels in the rainforest and in the more open areas. Results of analyses showed that canopy cover was critical for determining daily absorption/desorption. Fuels in the boundary and sclerophyll vegetation lost more moisture during the day but absorbed more at night. Differences in daily moisture relations lead to differences in fuel drying after rain. After 14 days without rain in summer, when rainforest fuels become flammable, sclerophyll fuels are twice as dry. The summer drying curve for litter in the boundary exhibited rapid drying. This may be due to the fact that summer meteorological records are from Site 1, and the open nature of the burnt site may have affected conditions at the boundary. After 23 or 24 days after rain in autumn, both sclerophyll forest and boundary fuels reach a moisture ratio of 0.80 (20% moisture), while the rainforest fuels are still at a ratio of 0.60 (40% moisture).

# Section 4. Leaf flammability experiment

## 4.1. Aims and Objectives

This section describes a leaf flammability experiment examining differences in the flammability of live and dead leaves from common trees, shrubs and herbs of the rainforest, and of the eucalypt dominated sclerophyll forest. Mature leaves, phyllodes and cladodes (referred to as leaves hereafter) were used in the test because they are usually the thinnest tissues on the plant and are often the first part of the plant that ignites in a fire (Gill and Moore, 1996). Leaves are also important because they vary greatly between species and are useful for defining differences in the flammability of different species (Gill and Moore, 1996). Past research suggests that there may be differences in the flammability of living rainforest and sclerophyll leaves based on leaf moisture content or leaf chemistry, though this has not previously been examined (Pompe and Vines, 1966; Vines, 1981; Chandler *et al*., 1983; Whelan, 1995).

Increases in moisture content decrease the flammability of natural fuels (Pompe and Vines, 1966). In contrast to moisture relations in dead fuels, very little is known about the effects of moisture in live fuels on combustion. There can be differences in the flammability of leaves based on leaf chemistry: high energy organic compounds such as oils and waxes facilitate ignition at relatively low temperatures (Pompe and Vines,1966; King and Vines,1969). Plant species that dominate in open sclerophyll forest, such as *Eucalyptus,* contain large amounts of essential oils in leaves (Chandler *et al*., 1983). It is unknown if differences in the amount of volatile components effect the relative flammability of rainforest and sclerophyll leaves (Whelan, 1995). Another factor influencing combustion is the presence or absence of inorganic constituents in the fuels; it has been shown that the mineral content of plants affects flammability by causing the fuel to smolder rather than flame (King and Vines, 1969). This factor is potentially very important to fire suppression in rainforest because rainforest vegetation may have a higher mineral content (Vines, 1981).

The aim of this experiment was to test the flammability of rainforest and sclerophyll leaves, using the muffle furnace technique developed by Gill and Moore (1996). While there have been many experiments testing the flammability of leaves both living and dead, this is the first to focus specifically on differences between rainforest and sclerophyll forest. The specific objectives of the experiment were to measure the ignitability of leaves in two ways and then relate these to leaf characters.

One measure of flammability used was the ignition delay time (IDT), being the time it takes an individual leaf to ignite at a given temperature (Gill and Moore, 1996). The second measure of flammability used was derived by testing leaves from each species at a range of temperatures and estimating the temperature at which 50% fail to ignite. This measure was termed the 50% flammability threshold temperature (50%FTT), and was developed specifically for this experiment. The aim of the experiment was to test the responses of fresh and dry leaves separately. For analysis of the fresh specimens, leaf area, thickness, surface area to volume ratio, leaf moisture ratio and vegetation type were used as predictive variables. For the dry specimens leaf moisture ratio was not included.

## 4.2. Methods and materials

Samples were collected by selecting leaf bearing twigs from common rainforest and sclerophyll species within the Kioloa Flora Preserve (Kioloa State Forest). Live leaf samples were collected during June 1997 and on collection were placed in labeled plastic bags and stored in an insulated container to minimise water loss, a sample of leaves was oven dried at 75°C. Fresh leaves and oven dry leaves from each species were tested in the muffle furnace at a range of temperatures. At each temperature six leaves from each species were tested, except the lowest temperature where only three fresh and three dry replicates were used. For most species, whole leaves were used for the experiment. The leaves of monocots, including palms, were cut to lengths of 8.5 cm and species with very small leaves (<1cm long) were tested by using leaf covered branchlets.

Specimens were placed on a wire cradle 3.5 cm. above the floor of the muffle furnace. The door of the furnace remained open, a temperature gradient existed in the furnace and airflow occurred. The temperature just beneath where each specimen was placed was measured using a thermocouple probe. The ignitibility of samples was tested at probe temperatures of about 150°, 200°, 250° and 300°C. Oven temperatures were adjusted to achieve probe temperatures within 5°C of the required temperature. A high frequency electric spark gun (M. Gill, CSIRO) was used to ignite the leaf, the spark does not ignite a leaf at low temperatures, and prevents a heated leaf from charring without ignition. The gun was held so the spark contacted with the leaf.

Time to ignition was recorded using a stopwatch. If no ignition occurred within two minutes the sample was removed from the oven and the result was recorded as no flame. Analysis of IDT was conducted by comparing the response of fresh and dry leaves from each species at 300°C, leaves of all species except *Casuarina cunninghamiana* ignited at this temperature. The 50%FTT was calculated for each species by fitting logistic regression equations based on the number of specimens from each species that failed to ignite at each temperature. Leaf surface area was measured using a Paton electronic planimeter (CSIRO) in $mm^2$, leaf thickness was measured with a micrometer in mm, surface area to volume ratio was calculated as 2/thickness and leaf moisture was expressed as a ratio of wet weight/ dry weight.

## 4.3. Results

The leaf characteristics and ignitibility of 50 species from 30 families were tested (all are listed in Tables 4.1 and 4.3), of these 27 species were from the rainforest and 23 from the sclerophyll forest. Leaf characteristics are listed for each species in Table 4.1. Analysis of variance conducted on the fresh leaf characteristics indicates that there are significant differences between leaf thickness, area, surface area to volume (S/V ratio) and leaf moisture content between rainforest and sclerophyll species (Table 4.2). Rainforest leaves are larger and thinner than sclerophyll leaves, they have a larger surface area to volume ratio and are moister when fresh.

**Table 4.2** Means, standard errors and significance derived from ANOVA of fresh leaf surface area (mm$^2$), thickness (mm), surface area to volume ratio and moisture ratio in relation to vegetation type.

| | **Rainforest** | | **Sclerophyll** | | | | |
|---|---|---|---|---|---|---|---|
| **Term** | **Mean** | **s.e.** | **Mean** | **s.e.** | **R$^2$** | **F-ratio** | **Prob>F** |
| Area | 6492 | 690 | 1972 | 747 | 0.29 | 19.74 | 0.0000 |
| Thickness | 0.21 | 0.03 | 0.36 | 0.03 | 0.20 | 12.04 | 0.0011 |
| S/V ratio | 9.74 | 0.43 | 7.28 | 0.46 | 0.35 | 17.52 | 0.0001 |
| Moisture | 2.91 | 0.10 | 2.47 | 0.10 | 0.16 | 9.29 | 0.0037 |

Table 4.3 shows the average IDT and standard error for each species at 300°C. Where specimens failed to ignite within two minutes at this temperature, means for the species were estimated by survivorship analysis incorporating censorship of the specimens that that did not ignite. The effect of leaf characteristics and forest type on IDT at 300°C were examined separately for fresh and dry specimens using multiple regression. The results from these analyses are shown in Tables 4.4 and 4.5. Logarithmic transformation of IDT was necessary because variation increased with IDT. It was necessary to exclude certain outliers from both the fresh and dry analyses, these were monocot tussocks and small leaved species which all exhibited an exaggerated response having very a high IDT in relation to leaf thickness or leaf area. Analysis showed that leaf thickness and leaf area were both significant to predicting the IDT of dry specimens, but that only leaf thickness was significant to predicting the IDT of fresh specimens. IDT increased with increases in leaf area and thickness but decreased with moisture content. ANOVA comparing IDT of all specimens (fresh and dry) in relation to vegetation type showed that rainforest species have lower IDT at 300°C than sclerophyll species. Mean IDT and standard errors for both forest types are shown in Figure 4.1, as can be seen little variation was explained by this model, estimates of significance are as follows: $R^2 = 0.04$, F-ratio= 3.75, Prob>F= 0.057.

**Table 4.4** Results of multiple regression analysis showing the significance of leaf thickness, surface area and moisture ratio in predicting $Log_{10}$ IDT of fresh specimens.

**$R^2$= 0.30, F-ratio= 5.85, Prob>F= 0.0020**

| Term | Est. | s.e. | F-ratio | Prob>F |
|---|---|---|---|---|
| Thickness (mm) | 0.50 | 0.12 | 9.56 | 0.0036 |
| Surface area ($mm^2$) | -0.01 | 0.01 | 3.63 | 0.0637 |
| Moisture ratio | 0.06 | 0.03 | 3.48 | 0.0692 |

**Table 4.5** Results of multiple regression analysis showing significance of leaf thickness and surface area in predicting $Log_{10}$ IDT of fresh specimens.

**$R^2$= 0.56, F-ratio= 30.41, Prob>F= 0.0000**

| Term | Est. | s.e. | F-ratio | Prob>F |
|---|---|---|---|---|
| Thickness (mm) | 0.21 | 0.19 | 11.12 | 0.0018 |
| Surface area ($mm^2$) | -0.01 | -0.01 | 32.49 | 0.0000 |

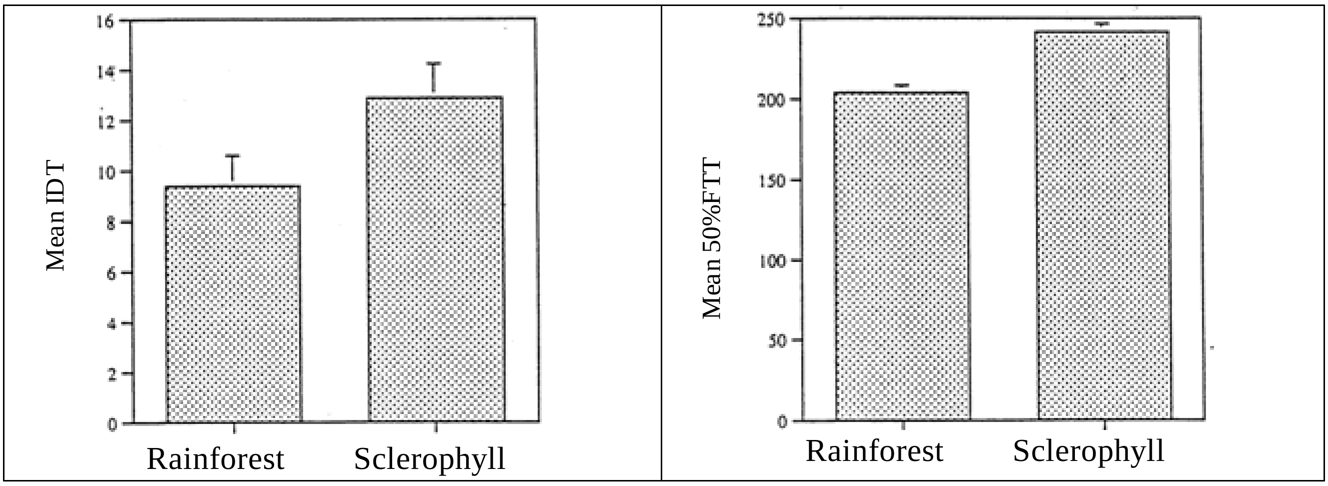


**Figure 4.1** Mean IDT and 50%FTT , and standard errors for all specimens (fresh and dry) of species from the rainforest and sclerophyll forest.

**Table 4.1** Fresh and dry leaf characteristics for species tested in leaf flammability experiment. Species identification after Harden (1993).

| Family | Species | Forest Type | Surface Area ($mm^2$) | Fresh Thick. mm | Fresh Surf./ Vol | Dry Thick (mm) | S/N Ratio | Ratio Live/ Dead |
|---|---|---|---|---|---|---|---|---|
| Anacardiaceae | *Synoum glandulosum* | Rf | 6466 | .20 | 9.85 | 0.10 | 20.41 | 3.65 |
| Arecaceae | *Archontophoenix cunninghamiana* | Rf | 4492 | 0.16 | 12.58 | 0.10 | 20.00 | 3.60 |
| Arecaceae | *Livistona australis* | Rf | 4925 | 0.17 | 11.49 | 0.12 | 17.24 | 2.31 |
| Asclepiadaceae | *Marsdenia suberosa* | Rf | 7117 | 0.24 | 8.26 | 0.10 | 19.23 | 3.62 |
| Aspleniaceae | *Asplenium polydon* | Rf | 958 | 0.23 | 8.70 | 0.15 | 13.33 | 2.91 |
| Asteraceae | *Helichrysum diomifolium* | Scler | 50 | 0.18 | 11.11 | 0.15 | 13.07 | 2.53 |
| Blechnaceae | *Blechnum cartilagineum* | Rf | 3976 | 0.21 | 9.39 | 0.15 | 13.25 | 3.00 |
| Casuarinaceae | *Casuarina cunninighamian* | Scler | 181 | 0.60 | 6.66 | 0.47 | 8.52 | 2.22 |
| Cunoniaceae | *Cerapetalum apetalum* | Rf | 12606 | 0.25 | 7.94 | 0.16 | 12.66 | 3.01 |
| Cunoniaceae | *Callicoma serratifolia* | Rf | 13757 | 0.17 | 11.83 | 0.13 | 15.15 | 2.13 |
| Cunoniaceae | *Schizomeria ovata* | Rf | 16030 | 0.28 | 7.14 | 0.15 | 13.33 | 2.67 |
| Cyperaceae | *Lepidosperma urophorum* | Scler | 122 | 0.72 | 5.52 | 0.59 | 6.74 | 2.40 |
| Cyperaceae | *Ghania radula* | Scler | 2117 | 0.25 | 8.10 | 0.22 | 9.01 | 1.75 |
| Dennstaedtiaceae | *Pteridium esculentum* | Scler | 3392 | 0.21 | 9.57 | 0.15 | 13.51 | 2.85 |
| Dicksoniaceae | *Dicksonia antarctica* | Rf | 1448 | 0.19 | 10.31 | 0.11 | 18.87 | 1.98 |
| Dilleniaceae | *Hibbertia aspera* | Scler | 300 | 0.22 | 9.17 | 0.12 | 16.13 | 2.91 |
| Elaeocarpaceae | *Elaeocarpus reticulatus* | Rf | 4574 | 0.26 | 7.58 | 0.21 | 9.62 | 2.15 |
| Epacridaceae | *Leucopogon lanceolatus* | Scler | 310 | 0.21 | 9.57 | 0.15 | 13.33 | 2.08 |
| Euphorbiaceae | *Breynia oblongifolia* | Scler | 1306 | 0.30 | 6.73 | 0.20 | 10.20 | 2.32 |
| Fabaceae | *Pultenaea blakelyi* | Scler | 50 | 0.30 | 6.67 | 0.25 | 8.00 | 2.30 |
| Fabaceae | *Pultenaea villosa* | Scler | 10 | 35 | 5.71 | 0.09 | 23.53 | 2.31 |
| Lamiaceae | *Prostanthera lasianthos* | Rf | 3564 | 0.21 | 9.35 | 0.14 | 14.39 | 3.65 |
| Lamiaceae | *Prostanthera violacea* | Scler | 56 | 0.19 | 10.53 | 0.14 | 14.60 | 2.99 |
| Lauraceae | *Cryptocarpa glaucescens* | Rf | 8750 | 0.18 | 11.30 | 0.18 | 11.05 | 2.22 |
| Mimosaceae | *Acacia floribunda* | Scler | 741 | 0.21 | 9.76 | 0.14 | 14.49 | 2.36 |
| Mimosaceae | *Acacia mabellae* | Scler | 4345 | 0.24 | 8.33 | 0.13 | 15.15 | 2.08 |
| Mimosaceae | *Acacia longifolia* | Scler | 2005 | 0.40 | 5.01 | 0.16 | 12.66 | 2.54 |
| Monimiaceae | *Doryphora sassafras* | Rf | 7871 | 0.29 | 6.85 | 0.15 | 13.16 | 3.23 |
| Monimiaceae | *Palmaria scandens* | Rf | 11752 | 0.16 | 12.27 | 0.11 | 17.54 | 3.59 |
| Moraceae | *Malaisia scandens* | Rf | 8292 | 0.17 | 11.83 | 0.10 | 19.23 | 2.99 |
| Moraceae | *Ficus obliqua* | Rf | 7660 | 0.22 | 9.09 | 0.10 | 20.83 | 2.76 |
| Myrtaceae | *Acmena smithii* | Rf | 7226 | 0.22 | 9.26 | 0.12 | 16.39 | 3.03 |
| Myrtaceae | *Backhousia myrtifolia* | Rf | 3392 | 0.21 | 9.62 | 0.15 | 13.70 | 2.18 |
| Myrtaceae | *Rhodamnia rubescens* | Rf | 3234 | 0.23 | 8.85 | 0.19 | 10.53 | 1.99 |
| Myrtaceae | *Tristaniopsis collina* | Rf | 4428 | 0.30 | 6.58 | 0.18 | 10.99 | 2.48 |
| Myrtaceae | *Eucalyptus pilularis* | Scler | 4208 | 0.21 | 9.52 | 0.13 | 15.38 | 2.21 |
| Myrtaceae | *Eucalyptus maculata* | Scler | 10960 | 0.30 | 6.76 | 0.22 | 9.26 | 1.97 |
| Myrtaceae | *Leptospermum flavescens* | Scler | 70 | 0.27 | 7.41 | 0.18 | 11.36 | 2.13 |
| Myrtaceae | *Eucalyptus botryoides* | Scler | 12124 | 0.30 | 6.58 | 0.14 | 14.29 | 2.47 |
| Philesiaceae | *Eustrephus latifolius* | Rf | 2147 | 0.15 | 13.51 | 0.11 | 18.52 | 2.84 |
| Poaceae | *Panicum simile* | Scler | 190 | 1.12 | 3.58 | 0.96 | 4.16 | 2.54 |
| Proteaceae | *Persoonia liniaris* | Scler | 532 | 0.41 | 4.91 | 0.18 | 11.05 | 3.18 |
| Proteaceae | *Banksia spinulosa* | Scler | 216 | 0.48 | 4.21 | 0.38 | 5.32 | 2.11 |
| Rubiaceae | *Morinda jasminoides* | Rf | 3203 | 0.12 | 16.39 | 0.08 | 26.32 | 3.37 |
| Santalaceae | *Exocarpus cupressiformus* | Scler | 94 | 0.55 | 7.24 | 0.31 | 12.74 | 2.70 |
| Smilacaceae | *Smilax australis* | Rf | 9470 | 0.28 | 7.09 | 0.18 | 11.11 | 3.15 |
| Verbenaceae | *Clerodendrum tomentosum* | Rf | 8437 | 0.19 | 10.70 | 0.11 | 17.70 | 3.79 |
| Vitaceae | *Cissus hypoglauca* | Rf | 4117 | 0.27 | 7.52 | 0.18 | 11.11 | 3.06 |
| Winteraceae | *Tasmannia insipida* | Rf | 5398 | 0.26 | 7.69 | 0.10 | 19.80 | 3.17 |
| Xanthorrhoeaceae | *Lomandra longifolia* | Scler | 1979 | 0.40 | 4.98 | 0.25 | 8.13 | 3.67 |

**Table 4.3** Mean IDT and standard errors, 50%FTT and 95%C.I. for species tested in the leaf flammability experiment. Species identification after Harden (1993).

| Family | Species | Forest Type | IDT Fresh | se IDT Fresh. | IDT Dry | se IDT Dry | 50%FTT Fresh | 50%FTT Dry | 95% C.I. |
|---|---|---|---|---|---|---|---|---|---|
| Anacardiaceae | *Synoum glandulosum* | Rf | 16.5 | 0.6 | 2.87 | 0.22 | 240 | 205 | 50 |
| Arecaceae | *Archontophoenix cunninghamiana* | Rf | 16.32 | 0.77 | 2.85 | 0.17 | 210 | 210 | 5 |
| Arecaceae | *Livistona australis* | Rf | 18.31 | 0.94 | 3.18 | 0.18 | 232 | 185 | 50 |
| Asclepiadaceae | *Marsdenia suberosa* | Rf | 10.71 | 0.68 | 1.13 | 0.12 | 190 | 175 | 25 |
| Aspleniaceae | *Asplenium polydon* | Rf | 21.42 | 0.71 | 4.40 | 0.24 | 250 | 225 | 60 |
| Asteraceae | *Helichrysum diomifolium* | Scler | 12.16 | 0.96 | 2.97 | 0.29 | 230 | 230 | 20 |
| Blechnaceae | *Blechnum cartilagineum* | Rf | 9.80 | 0.58 | 3.31 | 0.44 | 280 | 280 | 20 |
| Cunoniaceae | *Cerapetalum apetalum* | Rf | 12.32 | 0.55 | 2.34 | 0.21 | 172 | 172 | 18 |
| Cunoniaceae | *Callicoma serratifolia* | Rf | 9.85 | 0.19 | 1.87 | 0.21 | 205 | 180 | 55 |
| Cunoniaceae | *Schizomeria ovata* | Rf | 13.30 | 0.62 | 1.81 | 0.12 | 218 | 175 | 30 |
| Cyperaceae | *Lepidosperma urophorum* | Scler | 26.22 | 3.33 | 9.53 | 0.81 | 278 | 278 | 17 |
| Cyperaceae | *Ghania radula* | Scler | 34.29 | 1.26 | 7.49 | 0.76 | 232 | 185 | 50 |
| Dennstaedtiaceae | *Pteridium esculentum* | Scler | 22.98 | 1.50 | 5.82 | 0.25 | 213 | 213 | 60 |
| Dicksoniaceae | *Dicksonia antarctica* | Rf | 20.16 | 0.03 | 19.19 | 3.11 | 240 | 264 | 60 |
| Dilleniaceae | *Hibbertia aspera* | Scler | 17.92 | 0.88 | 8.61 | 1.24 | 297 | 282 | 20 |
| Elaeocarpaceae | *Elaeocarpus reticulatus* | Rf | 11.44 | 0.95 | 3.13 | 0.38 | 179 | 179 | 22 |
| Epacridaceae | *Leucopogon lanceolatus* | Scler | 11.31 | 18.10 | 12.87 | 23.03 | 320 | 302 | 42 |
| Euphorbiaceae | *Breynia oblongifolia* | Scler | 18.80 | 0.54 | 6.68 | 0.26 | 235 | 255 | 75 |
| Fabaceae | *Pultenaea blakelyi* | Scler | 15.10 | 1.32 | 6.46 | 1.29 | 278 | 278 | 20 |
| Fabaceae | *Pultenaea villosa* | Scler | 18.61 | 0.89 | 4.72 | 0.12 | 202 | 220 | 40 |
| Lamiaceae | *Prostanthera lasianthos* | Rf | 10.68 | 1.05 | 2.94 | 0.17 | 280 | 280 | 21 |
| Lamiaceae | *Prostanthera violacea* | Scler | 17.21 | 0.88 | 3.00 | 0.17 | 190 | 119 | 60 |
| Lauraceae | *Cryptocarpa glaucescens* | Rf | 12.61 | 0.40 | 3.14 | 0.17 | 180 | 229 | 25 |
| Mimosaceae | *Acacia floribunda* | Scler | 13.98 | 0.80 | 3.99 | 0.25 | 239 | 268 | 40 |
| Mimosaceae | *Acacia mabellae* | Scler | 13.08 | 0.56 | 3.43 | 0.26 | 255 | 210 | 60 |
| Mimosaceae | *Acacia longifolia* | Scler | 12.91 | 0.30 | 3.02 | 0.24 | 132 | 132 | 22 |
| Monimiaceae | *Doryphora sassafras* | Rf | 15.99 | 0.18 | 3.34 | 0.53 | 174 | 174 | 15 |
| Monimiaceae | *Palmaria scandens* | Rf | 16.92 | 0.58 | 1.93 | 0.14 | 1.97 | 205 | 50 |
| Moraceae | *Malaisia scandens* | Rf | 12.23 | 1.01 | 3.50 | 0.23 | 210 | 220 | 50 |
| Moraceae | *Ficus obliqua* | Rf | 23.00 | 1.12 | 3.44 | 0.14 | 220 | 173 | 20 |
| Myrtaceae | *Acmena smithii* | Rf | 13.60 | 0.83 | 3.04 | 0.18 | 190 | 180 | 32 |
| Myrtaceae | *Backhousia myrtifolia* | Rf | 16.15 | 0.70 | 3.00 | 0.18 | 200 | 192 | 40 |
| Myrtaceae | *Rhodamnia rubescens* | Rf | 12.43 | 0.23 | 2.96 | 0.22 | 208 | 175 | 60 |
| Myrtaceae | *Tristaniopsis collina* | Rf | 14.38 | 0.49 | 2.89 | 0.16 | 200 |  | 15 |
| Myrtaceae | *Eucalyptus pilularis* | Scler | 11.73 | 0.48 | 3.09 | 0.27 | 180 | 180 | 22 |
| Myrtaceae | *Eucalyptus maculata* | Scler | 12.05 | 0.57 | 2.47 | 0.17 | 175 | 175 | 20 |
| Myrtaceae | *Leptospermum flavescens* | Scler | 21.63 | 2.97 | 5.44 | 0.16 | 248 | 233 | 23 |
| Myrtaceae | *Eucalyptus botryoides* | Scler | 13.14 | 0.63 | 1.68 | 0.22 | 180 | 180 | 20 |
| Philesiaceae | *Eustrephus latifolius* | Rf | 12.86 | 0.55 | 3.71 | 0.37 | 215 | 230 | 50 |
| Poaceae | *Panicum simile* | Scler | 46.84 | 7.19 | 5.54 | 0.67 | 278 | 278 | 20 |
| Proteaceae | *Persoonia liniaris* | Scler | 19.13 | 0.74 | 3.11 | 0.25 | 230 | 230 | 20 |
| Proteaceae | *Banksia spinulosa* | Scler | 20.25 | 1.45 | 4.98 | 0.38 | 280 | 280 | 30 |
| Rubiaceae | *Morinda jasminoides* | Rf | 21.89 | 1.79 | 3.90 | 0.29 | 258 | 220 | 70 |
| Santalaceae | *Exocarpus cupressiformus* | Scler | 25.24 | 1.59 | 7.93 | 2.10 | 260 | 275 | 20 |
| Smilacaceae | *Smilax australis* | Rf | 23.58 | 0.82 | 3.05 | 0.40 | 174 | 174 | 20 |
| Verbenaceae | *Clerodendrum tomentosum* | Rf | 12.33 | 0.79 | 1.63 | 0.14 | 208 | 165 | 10 |
| Vitaceae | *Cissus hypoglauca* | Rf | 15.36 | 0.83 | 2.18 | 0.10 | 203 | 210 | 50 |
| Winteraceae | *Tasmannia insipida* | Rf | 13.25 | 0.59 | 2.69 | 0.44 | 179 | 179 | 20 |
| Xanthorrhoeaceae | *Lomandra longifolia* | Scler | 49.27 | 3.77 | 7.34 | 1.37 | 230 | 203 | 20 |

Mean IDT and 50%FTT for fresh and dry specimens of all species are shown in Table 4.3, 95% C.I. estimated from logistic curves are given as the measure of variation about the mean. Dry specimens of *Tristaniopsis collina* have a 50%FTT <150°C and *Casurina cunninghamiana* has a 50%FTT> 300°C. The results from multiple regression predicting 50%FTT of fresh and dry specimens from leaf characteristics and forest type are shown in Table 4.6. For both fresh and dry specimens the square root of leaf surface area was the only significant variable, 50%FTT decreased with increases in the square root of leaf surface area. Means and standard errors from analysis of variance comparing 50%FTT for all specimens (fresh and dry) in relation to vegetation type are shown in Figure 4.1. Rainforest species have a lower 50%FTT• than sclerophyll species ($R^2$ = 0.23, F-ratio= 29.49, Prob>F= 0.0000).

**Table 4.6** Results of regression analyses using square root of leaf area to predict the 50%FTT of fresh and dry specimens.

| Fresh/Dry | Est. | s.e. | $R^2$ | F-ratio | Prob>F |
|---|---|---|---|---|---|
| Fresh | -0.74 | 0.11 | 0.47 | 43.13 | 0.0000 |
| Dry | -0.88 | 0.11 | 0.60 | 69.67 | 0.0000 |

## 4.4. Discussion

This experiment has shown that the ignitability characteristics measured are strongly related to leaf surface area which was significant for predicting the 50%FTT of both fresh and dry specimens and for predicting the IDT of dry specimens. Leaf surface area was not significant for predicting the IDT of fresh specimens. Analysis of the 50%FTT shows that the square root of surface area was a better predictor than surface area. This indicates that ignitability increases with increases in the width of the leaf.

Differences in flammability due to the effect of leaf area may be explained in terms of the physics of heating. A leaf in the muffle furnace was subjected to radiant heating from the walls of the furnace but because the door of the furnace remained open, it was also subject to cooling from air from outside which was drawn into the furnace by convection. Past work on heat loss in leaves has shown that when a leaf is heated by radiation, a temperature gradient will exist within the leaf: air flow cools a leaf most near the margins and so a leaf heats more slowly near the edges (Montieth, 19'73). This means that a larger leaf, when placed horizontally in a muffle furnace, will not lose as much heat at its centre as does a small leaf and will ignite faster, or at a lower furnace temperature. This experiment has shown that larger leaves do ignite faster and burn at lower furnace temperatures than smaller leaves, and that the temperature at which a leaf will fail to burn in the muffle furnace is determined by the width of the leaf.

The importance of leaf area in governing the ignitability of leaves leads to general differences between the flammability of leaves from rainforest and sclerophyll species. Analysis of leaf characters with respect to forest type shows that the leaves from species of the rainforest are larger than those of species from the eucalypt dominated sclerophyll forest. Analysis of variance comparing the mean IDT and 50%FTT for rainforest and sclerophyll species (Figure 4.1) showed that rainforest leaves had a slightly lower IDT and a much lower 50%FTT. This work has shown that the factors governing the flammability of leaves is related to leaf dimensions and that rainforest leaves are slightly more flammable than sclerophyll leaves. These results do not lend much support to the theory that rainforest leaves will be less flammable than sclerophyll leaves because of differences in leaf moisture content or leaf chemistry. It is important to note, however, that while the small leaves of the sclerophyll forest are slow to ignite in the muffle furnace this may not represent what occurs during a bushfire. During a bushfire temperatures would be high enough to ignite even the smallest of leaves, under these conditions finer material may be faster to ignite due to aeration.

# Section 5. The direct effect of green foliage on fire spread.

## 5.1. Aims and objectives.

This experiment was designed to examine the effects that live foliage may have on fire behaviour, in particular, the role of rainforest boundary species such as broad leaved vines that may suppress fire by reducing the effect of radiation on fuel preheating. The most important factor operating to preheat and dry fuel during a fire and so promote forward spread is the efficient transfer of radiation from flames (Luke and McArthur, 1978). It is because of this that the slope and wind have a strong influence on forward spread (Vines, 1981; Luke and McArthur, 1978; Pompe and Vines, 1966). Radiation penetration would be decreased by an increase in the density of vegetation, and this experiment was designed to examine if this effect was obvious during an experimental burn. The suppressive effects of the vegetation would be increased if the vegetation was very wet. The presence of water vapour within a flame lowers its radiant heat output, the smoke created by water vapour also intercepts radiation (Pompe and Vines, 1966).

The experiment was designed to compare fire spread between areas of sclerophyll forest with a tussock monocot understorey and sclerophyll shrubs with adjacent areas, where a fence, draped in fresh green vines, was placed shortly before the fire. In this way, the experiment tests the impact of vines on the spread, or extinction of, fire with normal sclerophyll fuel loads and humidity. Vine densities on the fences were intended to represent typical and high densities of vine. In their natural settings, the vines would also affect the ground fuel loads and their moisture contents, typically reducing the growth of ground plants and increasing moisture content of the litter. In effect, the experiment was intended to focus only on the possible direct fire retarding properties of the green rainforest boundary foliage.

## 5.2. Methods and materials

The site for this experiment was a north facing slope, next to Spotted Gum Rd in Kioloa State Forest (35°15'35S" ,150 ° 17'00"E). The upper slope, with a gradient of 5-10°, was dominated by sclerophyll vegetation; further downslope, the incline increased to 10-20° and there was a transition into rainforest vegetation. Six wire fences, each 1 m high and 10 m long with gaps of about 20 m between, were established between trees: four on the upper slope, and two on the lower slope. Details of each fence are given in Table 5.1. The fences, and ground in front of the fences, were draped with *Cissus hypoclauca* a common vine of boundary and rainforest vegetation in south coastal N.S.W. which creeps over the ground and scrambles over low vegetation. Fences were covered with either a typical, or high density covering of fresh foliage bearing branches; typical densities were 50-70% (3 kg $m^{-1}$) of horizontal interception, while high density fences had a horizontal interception c.95% (4.4 kg $m^{-1}$). Firebreaks were created, running in a semicircular fashion 3-5 m behind each fence to clarify results by preventing the fire backburning through the fences. The fences were established 50-100 m downslope from where a fire was ignited at 13:00 on 1st May 1997; details of conditions at the fire front are given in the Results. A downslope fire represents typical conditions where rainforest is situated downslope from sclerophyll vegetation.

After the fire had been lit, its progress up to, and past the fences, was monitored. A number of variables were measured in order to correctly assess the intensity of the fire at the study site. The direction and speed of the wind, relative humidity, air temperature, the rate of forward spread of the fire, flame height, and flame angles were recorded. Estimates of the suppressive ability of the vine fences were made by recording what proportion of the fences remained unburned by the fire, as well as how many times and where fire penetrated each fence.

## 5.3. Results

Conditions at the fire front are described in Figure 5.1; when the fire was lit at 13:00, 1/5/97, the air temperature was 23° C, and the relative humidity was 70%. The wind was blowing from the north against the direction of the fire, at a speed of 1 m $s^{-1}$, and flames were directed upslope to the south. The moisture content of the fuel when the fire was lit was measured at 15% (of dry weight) in the sclerophyll forest upslope, and 21% in the rainforest boundary downslope. Dry fuel loads were about 1.2 kg $m^{-2}$ upslope, and 1 kg $m^{-2}$ downslope. Soon after the fire was lit, flame heights were 1-1.5 m, inclined at about 70° against the direction of forward spread (with the wind, direction).

The fire reached its maximum rate of spread (20-30 cm $min^{-1}$) after burning for three hours. The fire reached the fences between 16:50 and 18:15 (see Table 5.1), and it can be seen from Figure 5.1 that fire spread was at its maximum when the first fences were burned, and declined after that. This is because slope increased once the fire had burnt through the first fences, and because meteorological conditions changed in the evening. Wind speed and temperature fell, while relative humidity rose (see Figure 5.1) which would have lead to observed increases in litter moisture. Characteristics of the fences and their survivorship during the fire are given in Table 5.1 below. The fire continued to burn downslope past the fences, eventually extinguishing in the boundary at about 19:00 - 20:00 with litter moisture contents of 29%.

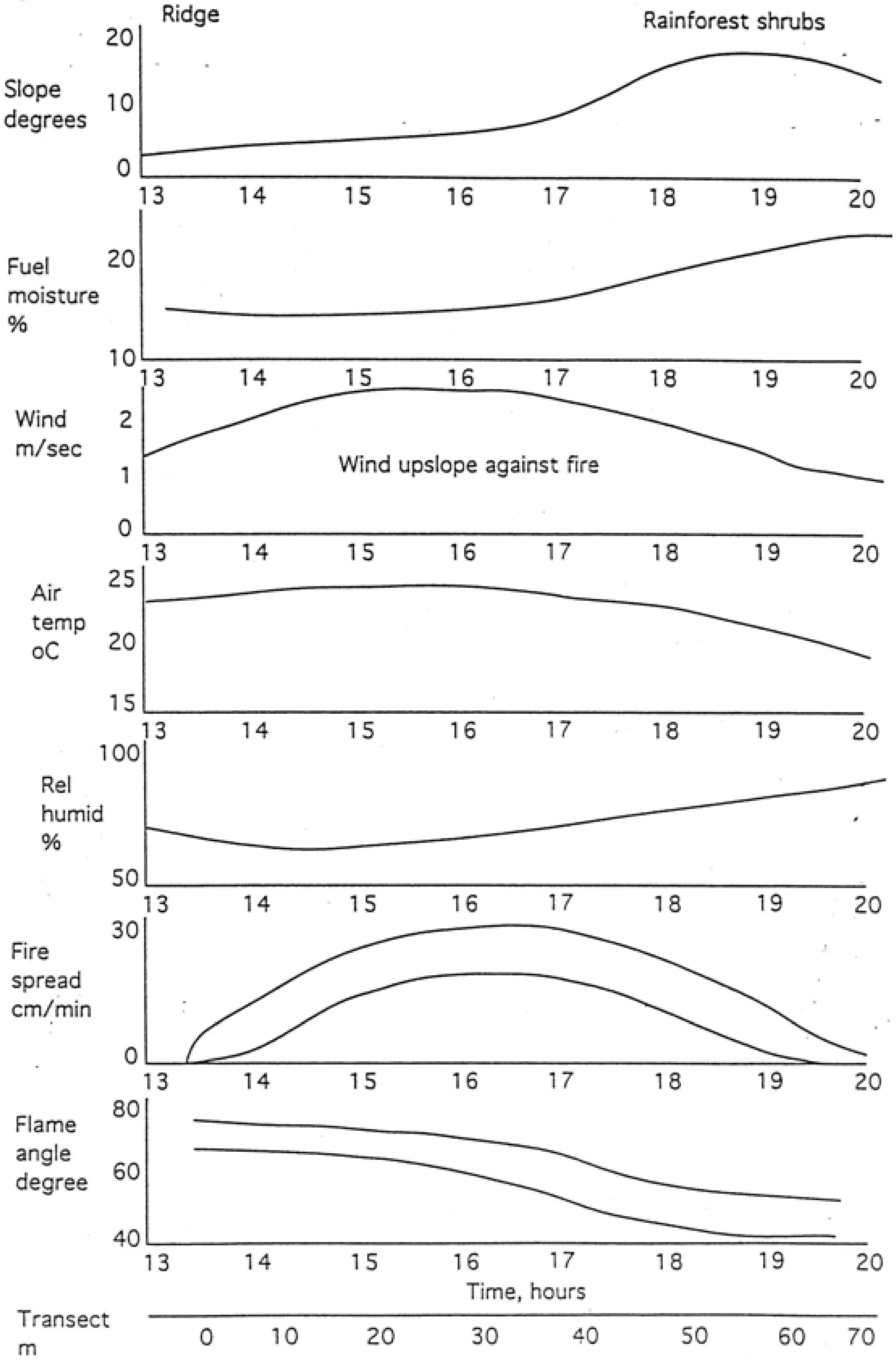


**Figure 5.1** Conditions at the fire front during the experimental burn at Spotted Gum Rd (Kioloa State Forest) on 1/5/97.

**Table 5.1** Characteristics of vine covered fences and of the fire impacts

| Time burnt | Slope° | Vine Density,% | Fire spread, cm $min^{-1}$ | Penetrated, no. times | Survived, % |
|---|---|---|---|---|---|
| 17:20 | 6 | 100 | 20 | 3 | 35 |
| 17:10 | 3 | 50 | 22 | 3 | 10 |
| 16:50 | 6 | 90 | 25 | 2 | 70 |
| 17:00 | 7 | 75 | 25 | 1 | 55 |
| 18:15 | 17 | 100 | 15 | 3 | 70 |
| 17:35 | 16 | 60 | 18 | 2 | 50 |

All fences were penetrated by fire at least once but on all fences there were lengths where green vines remained unburnt. The fire's progress through the fences was largely governed by the dry fine fuel that remained beneath the fences. Especially important were the dry dead leaves of monocot tussocks; as this fuel burned the vines above were wholly or partially ignited. Tables 5.2 and 5.3 show the results from multiple regression analysis for the number of times a fence was penetrated and for the percentage of freshly cut vine that remained unburnt on the fences. The results showed that the number of times a fence was penetrated was dependent upon the rate of forward spread (cm $min^{-1}$) at the time and on the slope (Table 5.1). The percentage of vines that remained unburnt on the fences was governed by an interaction between the above two variables and the density of the vine (Table 5.2).

The number of times a fence was penetrated decreased and the percentage of vine that survived on a fence increased with increases in the rate of forward spread of the fire (cm min $^{1}$), this effect may be explained because when a fast moving fire front penetrated the fence once it consumed all the sclerophyll fuel behind the fences very quickly and left fresh vines unburned along more of the length of the fence. The number of times a fence was penetrated decreased and the percentage of vine that survived on a fence increased with increases in slope, this result suggests that the vine covered fences also presented a barrier to fires with low rates of forward spread. The percentage of fresh vines that survived on a fence increased with increases in the percent cover of the vine on each fence which suggests that increases in the density of vine decrease the chance that it will all be burnt, although this result was not significant.

**Table 5.1** Significance of factors for predicting the number of times a fence was penetrated.

**$R^2$= 0.88, F-ratio= 11.31, Prob>F= 0.0401.**

| Term | Est. | s.e. | F-ratio | Prob>F |
|---|---|---|---|---|
| Fire spread, cm min$^{-1}$ | -0.32 | 0.07 | 22.60 | 0.0177 |
| Slope° | -0.17 | 0.05 | 13.51 | 0.0349 |

**Table 5.2** Significance of factors for predicting the percentage of fresh vine that remained unburned on fences.

**$R^2$= 0.95, F-ratio= 12.56, Prob>F= 0.0746.**

| Term | Est. | s.e. | F-ratio | Prob>F |
|---|---|---|---|---|
| Slope° | 4.89 | 1.02 | 23.05 | 0.0407 |
| Vine density, % | 0.63 | 0.17 | 12.75 | 0.0702 |
| Fire spread, cm min' | 5.84 | 1.51 | 15.00 | 0.0606 |

## 5.4. Discussion

This experiment has shown that green vines of the rainforest boundary have a direct effect on the extinguishment of fire, on all fences there remained areas where the freshly cut vines had not been burnt. Even when the fire was moving at its fastest large percentages of vines remained unburnt, at greater slopes the vines were also shown to have an increased suppressive effect on fire. An important result is that the percentage of vine that remained unburned increased with the percentage cover of vine on a fence. This implies that the density of the vine acts to intercept radiation by flames or to modify wind speeds and halts fire spread to adjacent fresh green leaves.

It is possible to conclude that the vines do have a suppressive effect on the spread of fire where dry fuel loads were low but it was observed that fire had been carried through the fences by the accumulation of dry litter and dry leaves of monocot tussocks that remained beneath the vines. This experiment showed that a single wall of vine is likely to be breached by fire if there are high levels of dry fuels and tussocks that can carry the fire. In their growing position vines would usually be associated with the reduced growth of understorey species and increases in the amount of shading and litter moisture. If vines occur between patches with high fuel loads, the results indicate that live vine foliage may cause fire extinguishment, though effects are likely to be dependant upon the intensity of the fire.

While these results suggest a suppressive effect they are not sufficiently detailed to allow development of a vegetation suppression index for use in the fire model. It is difficult to quantify the effect of vines in this way because, while it may be concluded that the vine leaves will increase the chance of extinguishment, the forward progress of the fire was clearly associated with the dryness of litter and the amount of tussock. The observed direct effects of the vine may be due to either modifications of radiation transfer or wind speed. The indirect effects of vines on fuel loads and moisture may substantially increase their affect, this is examined in the following chapter. It is possible to conclude from this experiment that vines may suppress fire and this is reason enough to further investigate their specific effects with a view to developing fire retardant vegetation barriers.

# Section 6. The extinguishment of fires and the damage they do.

## 6.1. Aims and objectives

This chapter describes vegetation surveys conducted at the sites of past fires to examine the effects of rainforest and boundary vegetation on fire and the effect of fire on the vegetation. The effects of vegetation on the spread of fires were investigated by surveying structural and fuel characteristics of the vegetation where fires of different intensities went out. The hypothesis was that fires of higher intensity will burn into vegetation of lower flammability. The intensity of the fire was estimated in adjacent burnt areas of sclerophyll forest which accurately reflects weather during the fire. Structural surveys conducted at the line of extinguishment should indicate the factors responsible for suppressing fire in rainforest or boundary vegetation. There are a number of ways that structural differences between the vegetation of rainforest and of sclerophyll forest may affect the intensity or forward progress of fire. The dense canopy of rainforest will affect fire weather and the moisture content of litter on the forest floor (Chapter 3), but there may be other structural factors that may lead to reductions in fire intensity such as the effect of dense vines as demonstrated in Chapter 5.

In rainforest and parts of the rainforest boundary there is a paucity of understorey shrubs, herbs and monocot tussocks that are common to open sclerophyll forest (Webb and Tracy, 1981b). These understorey components are an important contributor to fuel loads in sclerophyll forest (Howard, 1981). Understorey components may also have an important effect on the distribution of fine dead fuels. It is known that the distribution of fine fuel will affect the rate of spread of a fire, fuels that are more aerated will ignite faster and burn more rapidly than compacted fuels (McArthur, 1967; Luke and McArthur, 19'78; Cheney, 1981; Whelan, 1995). When there is an understorey, much litter will be aerated because it will be caught and supported by live vegetation. In contrast, rainforest litter is often more compacted because it is all on the ground (Howard, 1981). It is unknown if the presence of living understorey fuels or the contribution they make to aerating litter is directly responsible for differences in the flammability of sclerophyll forest and rainforest.

Surveys were also undertaken to examine the differential effects of fire on trees of the rainforest and the sclerophyll forest. This was done by recording the size and state (survived, killed or regenerated) of rainforest and sclerophyll trees in areas burnt within the last 4 years. Differences in the damage inflicted during fire or recovery after fire between trees from the two forest types is important for determining the recovery of the two forest types after fire and this may ultimately affect relative distributions. It is reported that rainforest trees may be more vulnerable to damage from fire than trees of the sclerophyll forest, especially eucalypts (Ashton, 1981b; Ash, 1988).

It is also known that rainforest species can coppice readily after fire (Stocker, 1981; Stocker and Mott, 1981; Unwin *et al* ., 1985; Unwin, 1989). The interaction between vulnerability to fire and coppicing ability may be an important determinate of the stability of rainforest boundaries (Unwin *et al*., 1985; Unwin, 1989).

## 6.2. Methods and materials

Both surveys were conducted at ten different sites within Kioloa and Brooman State Forests. In all cases fire burning from sclerophyll forest was extinguished in the rainforest or the rainforest boundary. The sites were chosen to cover a range of different fire intensities, including northern and southern slopes within areas burned by four recent fires. The locations approximate dates and weather conditions during the four fires examined are given in Table 6.1 below. The high intensity fire listed occurred during the very severe bushfire period of early 1994, which included some of the most severe fire weather conditions on record in N.S.W. The relative intensity of fire in the sclerophyll forest at each site was estimated by discussion with the Shoalhaven Group Captain (John Ashton) of the Rural Fire Service, by observation and by measuring scorch heights and the level of decortication by bark from smooth barked eucalypts, mainly *Eucalyptus maculates*. The field measures are accepted methods for conducting post fire surveys of fire intensity (McArthur and Cheney, 1966; Moore *et al.,* 1995; Whelan, 1995). An index of intensity was derived from the first axis of a principle components analysis of the scorch height, decortication depth and an ordinal term based on knowledge of the meteorological conditions prevailing during each fire and the aspect of individual sites. This principle components axis explained 80% of variation in the data set.

**Table 6.1** Locations, approximate dates and intensities for each fire where sites were surveyed.

| Location | Latitude | Longitude | Date | Intensity |
|---|---|---|---|---|
| Molloy' s Rd | 35°28'00S" | 150°16'00"E | January 1994 | Severe |
| Cousins Gully Rd | 35°34'30S" | 150° 19'20"E | April 1996 | Low |
| Dam Rd | 35°15'32S" | 150°118'30"E | April 1997 | Low |
| Spotted Gum Rd | 35°15'35S" | 150°17'00"E | May 199'7 | Moderate |

At each site structural surveys of the first meter of unburned vegetation were conducted along 50 m transects where the fire was extinguished. Sections along the transect where the structure of the vegetation was uniform were identified and surveyed individually. For each section within the transect the depth of the litter was measured and the cover provided by various classes of the vegetation was estimated. The classes included for surveying were as follows: tussock monocots (including grass), vines (0-1 m), shrubs (0-1 m), vines (1-4 m), shrubs (1-4 m), midstorey (4-10 m) and overstorey (>10 m). An estimate of the shade at the litter layer was also made. The effect of these different factors on where fires of different intensities were extinguished was examined using multiple regression.

To investigate differences in the damage caused by fire to trees from rainforest and sclerophyll forest, surveys were conducted along transects in areas that had been burnt at each site. The transects ran parallel to the vegetation boundary just upslope of where the fire went out. At each site 120 trees were surveyed and records made of species, the diameter at breast height (DBH) and whether the tree had survived the fire, was killed, or regenerated after the fire. Two measures of the impact of fires were investigated in relation to DBH; whether or not the tree had been killed by fire and whether or not the tree had been damaged by fire (which included those trees that were dead and resprouting). The responses of rainforest and sclerophyll trees were analysed separately using binomial logistic regression, and survivorship probabilities for the size (DBH) of the trees were generated.

## 6.3. Results

The line of extinguishment for fires of different intensities can be predicted from certain structural factors. Results of multiple regression analyses predicting the fire intensity index from the measured parameters of the structural surveys are shown in Tables 6.1 and 6.2. The best model showed that the fire intensity index decreased with the amount of monocot tussock and increased with increases in the midstorey (4-10 m) and the amount of vine (0-1 m). This indicates that fires of lower intensity are more likely to go out where there is still monocot tussock fuel and where there are few vines at low levels (0-1 m) or where there is a dense midstorey (4-10 m). The midstorey between four and ten meters is by far the most significant factor in this model .

**Table 6.1** Significance of factors in a multiple regression analysis for the fire intensity index.

**$R^2$= 0.26, F-ratio=9.13, Prob>F=0.0000**

| Term | Est. | s.e. | F-ratio | Prob>F |
|---|---|---|---|---|
| Monocot tussocks (%) | -0.02 | 0.01 | 6.71 | 0.0115 |
| Vines (0-1m) | 0.02 | 0.01 | 7.97 | 0.0060 |
| Midstorey (4-10m) | 0.02 | 0.01 | 14.98 | 0.0002 |

Examination of the predictions of this model reveals that the relationship is as shown in Figure 6.1. Evidently this model infringed assumptions about homogeneity of variance, but more importantly it suggests that the model needs refining. It was apparent that there is a threshold effect with predicted values ≥ observed values: this is the threshold flammability at which sites may suppress fire of a specific intensity (see Figure 6.1). This means that fires of low intensity may go out where the site conditions are of low to high flammability, but a high intensity fire only goes out only where site flammability is low. The threshold for fire extinguishment was, therefore, examined by only including the more flammable sites for a given fire intensity. The threshold sites were examined using multiple regression and this yielded a much stronger model ($R^2 = 0.59$) which also met the homogeneity of variance assumption. This model included more significant terms as shown in Table 6.2, it can be seen that the fire intensity index is greater where there are many vines, midstorey trees or shade at the point where the fires went out. The index decreased when there was deep litter and monocot tussocks, which means fires of high intensity did not go out in these areas.

**Table 6.2** Significance of factors in multiple regression analysis for predicting the fire intensity index for sites at the threshold of flammability.

**$R^2$ = 0.59, F-ratio = 14.97, Prob>F = 0.0000**

| Term | Est. | s.e. | F-ratio | Prob>F |
|---|---|---|---|---|
| Vines (0-1m) | 0.03 | 0.01 | 12.29 | 0.0010 |
| Midstorey (4-10m) | 0.01 | 0.01 | 5.81 | 0.0196 |
| Shade (%) | 0.02 | 0.01 | 6.38 | 0.0147 |
| Litter (cm) | -0.06 | 0.02 | 8.94 | 0.0043 |
| Monocot tussocks (%) | -0.03 | 0.01 | 22.65 | 0.0000 |

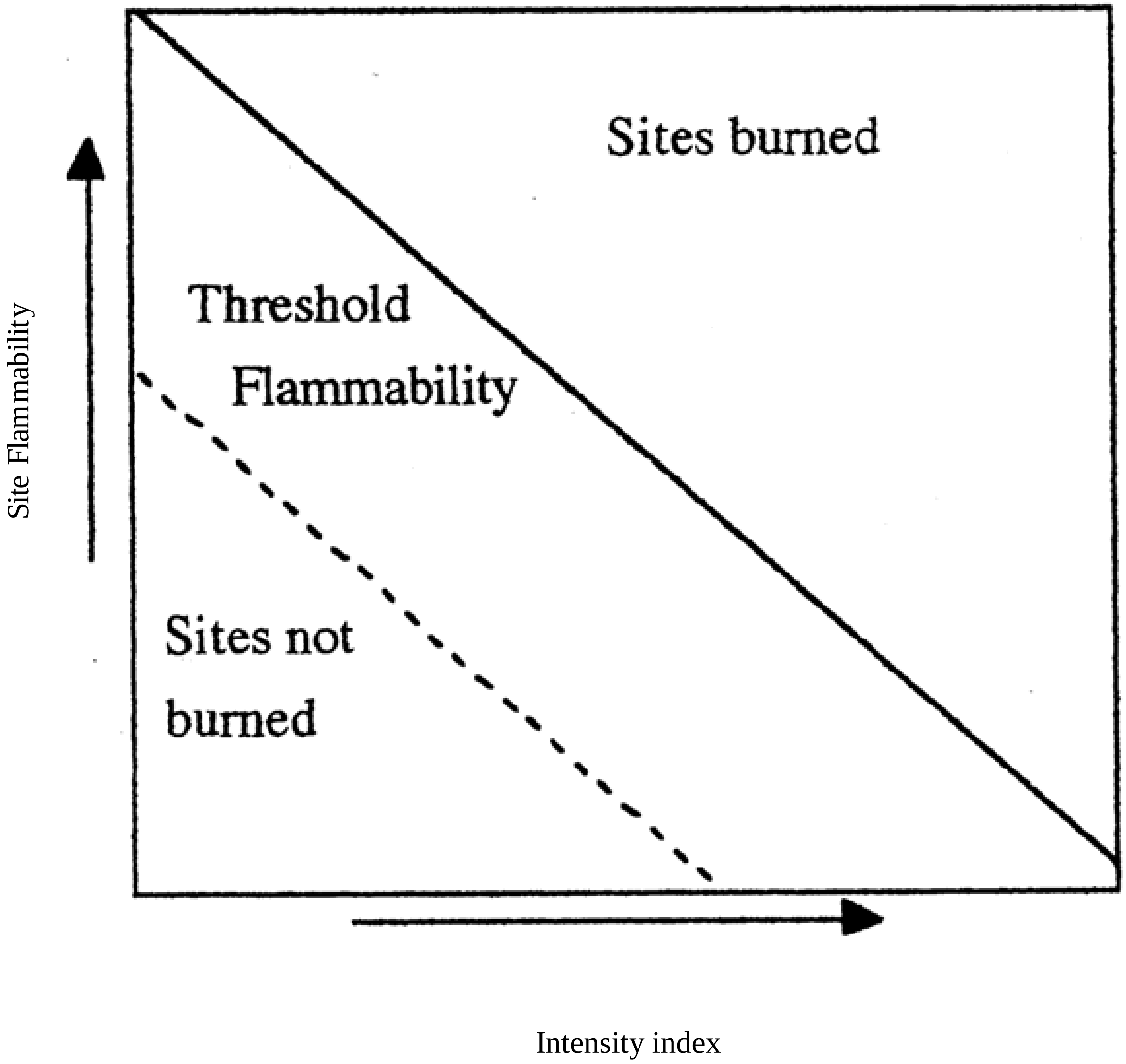


**Figure 6.1** Relationship between the estimated flammability of a site where the fire had extinguished, showing the threshold flammability at which fires of a specific intensity may be extinguished.

Results from the analysis of the impact of fire on rainforest and sclerophyll are shown in Figure 6.2. As expected, the probability that a tree will be killed or damaged by fire decreases with the size (DBH) of the tree. Results from comparison of trees that were damaged showed that there is very little difference in the probability of damage between rainforest and sclerophyll species for a specific DBH. Comparison of trees that were killed and those that survived showed that there were dramatic differences in the responses of rainforest and sclerophyll species. Rainforest trees are more liable to death when they are very small (<4 cm DBH) but the probability that they will be killed decreases rapidly with increases in DBH. Species of the sclerophyll forest exhibit a more gradual decrease in the probability of death with increases in DBH. The underlying reasons for these results are discussed in the next section.

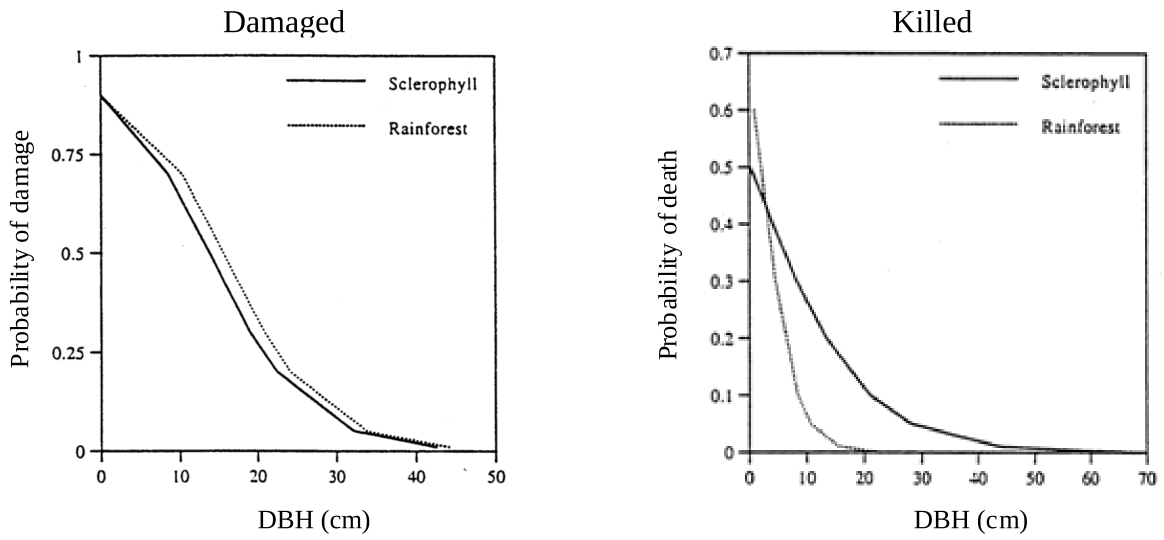


**Figure 6.2** Survivorship analysis of trees that were either damaged or killed in relation to vegetation type.

## 6.4. Discussion

Surveys conducted along the line of extinguishment of different fires showed that there are structural differences in the vegetation where fires of high and low intensity are extinguished. As hypothesised, more intense fires burnt vegetation of lower flammability. The line of extinction is comprised of vegetation below a flammability threshold. Fires of high intensity did not go out where there are monocot tussocks but they were extinguished in areas with a high cover of low vines (0-1 m) and/or small trees (4-10 m). Fires of high intensity were only extinguished where there was high shade and low levels of litter. These results have important implications for understanding the relative flammability of rainforest, rainforest boundaries and sclerophyll forest. There is a correlation between the effects of shade and the amount of litter and monocots present, this is because increased shade increases the moisture content of litter and dried tussock species. There is also a correlation between the amount of monocots and the depth of litter in sclerophyll forest that acts to promote fire. Only fires of low intensity will go out where there are high levels of litter and monocot tussocks, which means these factors promote fire spread when fuels are dry. These factors may interact to make areas with a monocot understorey far more flammable than areas without, due to the aeration of litter.

Vines at low levels (0-1 m) and midstorey trees (4-10 m) have been shown in these surveys to be present in high densities where fires of high intensities go out. The suppressive effects of the midstorey (4-10 m) are probably due to the effects of this structural class on shading and, therefore, litter moisture. The suppressive effects of vines at low levels may also be in part due to their effects on shading and fuel moisture but this result also appears to provide further evidence for suppressive effects occurring during fire (see Section 5). The specific effect of vines as shown in Table 6.2 suggests that vines at very high densities at low heights could suppress even a high intensity fire. This supports conclusions from the previous chapter that vines at high densities probably reduce radiation or wind speed during a fire and thus act to suppress fire. The results from this section do not indicate exactly how the effect of vines or other green foliage can be used to develop a vegetation suppression index. It is possible, however, to conclude that the vines do have a suppressive effect and this effect may be directly proportional to the amount of vine that is present.

Results from analysis of the impact of fire on trees of different sizes in relation to vegetation type showed that the probability of damage differed little between rainforest and sclerophyll species for any particular size. The probability of surviving a fire however differed greatly between rainforest and sclerophyll species. Rainforest trees were shown to be more liable to death at very low DBH (<4cm) but the probability that they would be killed decreased very rapidly with increasing DBH. This is due to the regeneration by coppicing rainforest trees with a DBH >4cm. Several species that form an important component of rainforest boundaries and mixed forest were all observed to be coppicing readily after fire, eg.: *Backhousia myrtifolia, Elaeocarpus reticulatus, Tristaniopsis collina, Synoum glandulosum* and *Callicoma serratifolia.*

The probability of death for sclerophyll species decreases much more slowly with increases in DBH than that of rainforest species; this is not what might be expected. Sclerophyll species respond in this way because of the inclusion of *Acacia mabellae.* This species is common in rainforest boundaries and mixed forest in south coastal N.S.W., and it was observed to be particularly vulnerable to death by fire, with trees of up to 20 cm DBH being killed at some sites. The results from DBH surveys confirm findings by (Stocker, 1981; Stocker and Mott, 1981; Unwin *et al.*,1995; Unwin, 1989) that rainforest trees coppice well after fire and this may mean that rainforest boundaries and mixed forest are stable after a single fire. There may, however, be long term impacts of repeated fires or specific fire regimes (Ash, 1988; Whelan, 1995) this needs to be studied further in relation to the relative distribution of rainforest and sclerophyll forest. Frequent fires will encounter young regrowth which was shown to be highly sensitive to fires. Conceptually, the probability that a rainforest tree will persist rises with increases in the fire interval in years.

# Section 7: Synthesis and discussion.

This section is in two parts, firstly the results of the previous chapters are drawn together by the use of the fire model (Section 7.1). In Section 7.2, the overall findings of the study are discussed in terms of their implications in regard to the role of fire in governing the distribution of temperate rainforest and rainforest boundaries, and in terms of managing or preventing fire in rainforest or in vegetation containing rainforest.

## 7.1. Application of the fire model.

The information collected in previous chapters on microclimate, fuel moisture and vines allows application of the fire model, outlined in the introduction, to quantify differences in the flammability of rainforest boundaries and sclerophyll forest. The flammability's of the different vegetation types were examined over 28 day periods following rain in summer and autumn, and over a single day of extreme fire weather. These represent typical weather conditions but for a prolonged rain free period and the impact of an infrequent but very severe fire weather day. The fire model was used to examine how the potential rate of forward spread of fire increased with fuel drying over the 28 day periods examined in Chapter 3. The model was run separately for each vegetation type based on the five minute predictions of the litter moisture model.

Certain parameters were standardised across vegetation types in order to derive direct comparisons of differences in rates of spread. Fuel loads in all vegetation types were standardised at 1 kg $m^2$; this is slightly higher than the means determined by field sampling (Chapter 3), but it is well within the normal range, and field sampling showed that there was very little difference between the amount of fine fuels on the ground in each vegetation type. Estimates of rates of forward spread at lower fuel loads will be directly proportional to those shown. Slope was set at -10°, this represents the typical situation where rainforest occurs downslope of open sclerophyll forest. The vegetation suppression index in the boundary was made directly proportional to the density of vine. To estimate differences in flammability based on the amount of creeping and scrambling vine at the boundary, the flammability estimates for the boundary are reduced by the amount of vine present (0-100% cover).

Potential rates of spread were also examined for the rainforest, the rainforest boundary and the sclerophyll forest during a day of extreme fire weather. Meteorological inputs for the high fire weather day were taken from weather records of conditions during the January 1939 fires which were some of the most severe on record in Australia (Luke and McArthur, 1978), more severe than the 1994 fires. Temperature, wind speed and relative humidity for the different vegetation types was estimated from the regression results of microclimatic sampling (Chapter 2).

Conditions for the sclerophyll forest were calculated from comparison with Kioloa, and then conditions in the boundary and rainforest were calculated from comparison with the sclerophyll forest. A normal PAR for a cloudless day in summer was used.

Daily minimum and maxima of microclimatic parameters for each vegetation type are shown in Table 7.1. Each variable was specified so that fire weather danger peaked at 15:00, when temperature and wind speed reached their maximum and relative humidity reached its minimum. The model was again run based on results of the litter moisture model over the day, a drying constant of 1.0 was used for this analysis to model fuel drying on such an intense fire weather day. Fuel load and slope were standardised as above. Potential maximum rates of fire spread achieved during the high fire weather day in each of the vegetation types was examined for different initial moisture ratios, which is the moisture content of the litter at the beginning of the day measured as dry wt. over wet wt.

**Table 7.1** Minimum and maximum meteorological conditions in each vegetation type during an extreme fire weather day.

| | **Sclerophyll** | | **Boundary** | | **Rainforest** | |
|---|---|---|---|---|---|---|
| **Parameter** | **Min.** | **Max.** | **Min** | **Max.** | **Min.** | **Max.** |
| Temperature (°C) | 15.8 | 38.1 | 15.8 | 37 | 15 | 36 |
| Relative humidity (%) | 10.4 | 30.6 | 14.2 | 34 | 19.4 | 39 |
| PAR (W $m^{-1}$) | 0.016 | 67.83 | 0.016 | 67.83 | 0.098 | 16 |
| Wind speed (m $s^{-1}$) | 0 | 2.66 | 0 | 1.1 | 0 | 1.1 |

The simulation of 28 day increases in rates of fire spread in the different vegetation types (Figure 7.1) shows that after a period of time without rain in summer, all vegetation types will become flammable. In autumn none of the three different vegetation types became flammable. With this analysis, rates of fire spread in the sclerophyll forest reach the fire threshold of 2-3 m $hr^{-1}$, below which a fire will not continue to burn, after 13 days without rain. Rates of forward spread in the rainforest reach this threshold after 21-22 days without rain. This analysis shows that there may be periods of over a week in summer when the sclerophyll forest is quite flammable, while the rainforest is not flammable. It is interesting to note that boundary flammabilities remain more like those of the rainforest during summer, even though they were shown to rise first. In this analysis the boundary reaches the fire threshold before sclerophyll forest. This is because site specific effects influenced litter moisture contents for the boundary (Chapter 3). After they reach the fire threshold, potential rates of forward spread in the sclerophyll forest rise very rapidly on a daily basis. Rates of spread in the rainforest and rainforest boundary do not rise as much even after they become flammable. It can be seen from the sclerophyll curve that flammabilities reach a plateau after increasing gradually over a few days, it appears that the rainforest is just reaching this plateau after 28 days without rain but it has stabilised with far lower daily peaks in rate of forward spread.

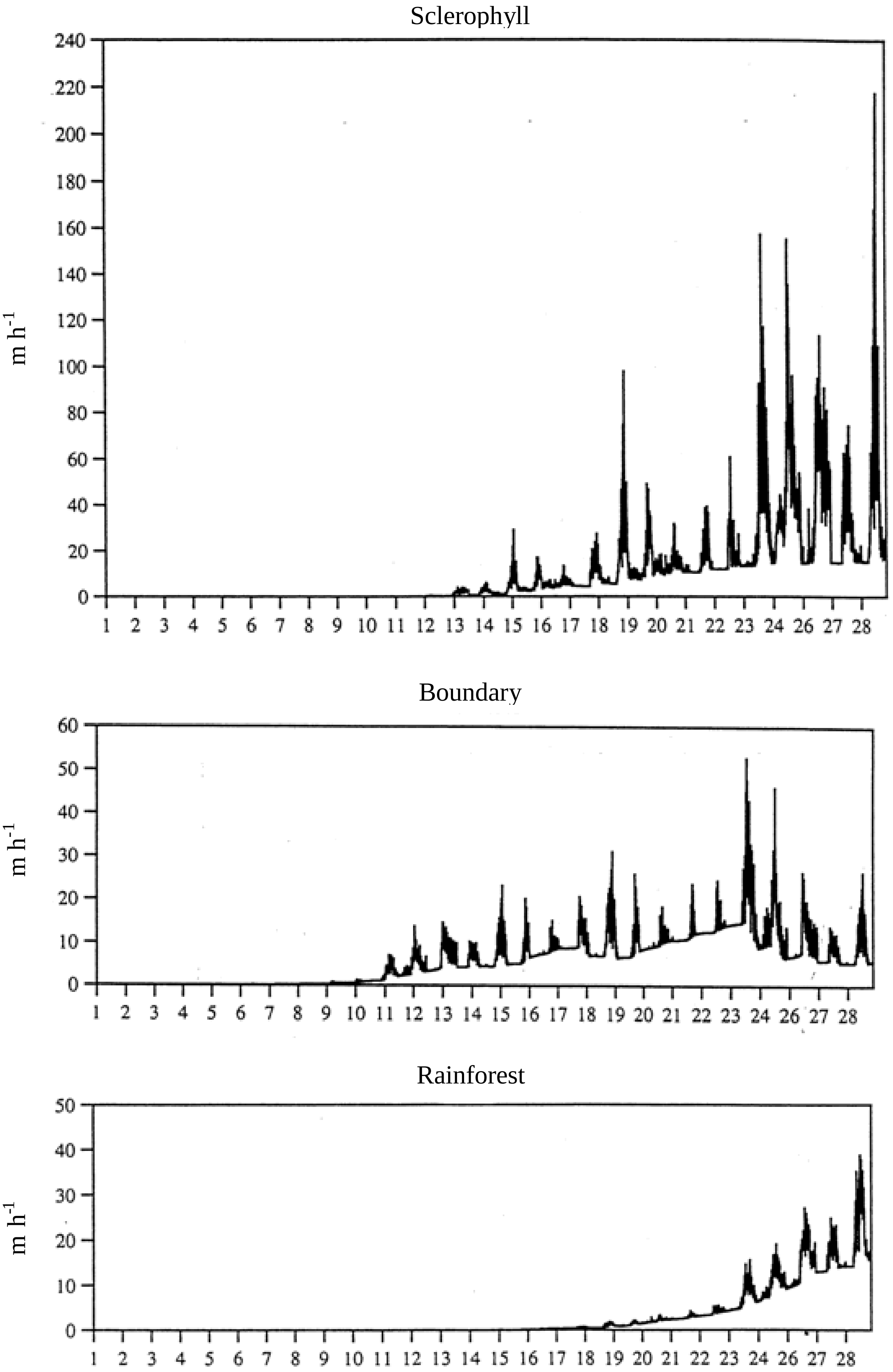


**Figure 7.1** Rises in potential rates of fire spread (Y axis) for the rainforest, the boundary and the sclerophyll forest with days after rain (X axis) in summer.

Analysis of rises in rates of forward spread in the different vegetation types during a day of extreme fire weather are shown in Figure 7.2. These results further support the finding that there are well defined differences in the flammabilities of the different forest types. It can be seen that rates of fire spread in the eucalypt forest are consistently above those of the rainforest and the rainforest boundary, especially when the moisture ratio is low at the start of the day. The sclerophyll forest becomes quite flammable during this day even when the fuel is moist at the start of the day (moisture ratio = 0.80), rates of forward spread peak at 65 m hr$^{-1}$. Rates of spread in the rainforest do not rise above the fire threshold when the moisture ratio is 0.80 at the start of the day, while the boundary was just flammable, having rates of spread of 6.5 m hr$^{-1}$. Rainforest and rainforest boundaries remain at relatively low flammability even under extreme fire weather conditions, when fuels are dry at the beginning of the day (moisture ratio=0.95) rates of spread in the rainforest reach 35.1 m hr$^{-1}$ and in the boundary they reach 37 m hr$^{-1}$, under these conditions rates of spread in the sclerophyll forest reach 270 m hr$^{-1}$ which is very severe.

The results from these simulations show that the differences in microclimatic conditions and the moisture contents of fuels in different vegetation types are responsible for well defined differences in flammability. The simulations show that all forest types will become flammable during extreme fire weather conditions but that rainforest and rainforest boundaries are less flammable than sclerophyll forest even under these conditions. From the analysis of rates of fire spread in summer it can be seen that the time the vegetation types reach the fire threshold roughly coincides with the time when litter in each reaches a moisture ratio of 0.09 (see Chapter 3). This shows that the difference in the rate of fuel drying in rainforest and sclerophyll forest is the most important factor determining their differences in flammability. Fuel moisture is determined by microclimatic conditions under a forest canopy (Chapter 3), the microclimate under a rainforest canopy is more buffered from changes in external conditions (Chapter 2), this is the reason why rates of fire spread do not rise as fast during the day or fall as much at night as in the sclerophyll forest.

The effect of canopy and microclimate on litter moisture is shown to be responsible for this effect: Chapter 3 showed that canopy differences lead to the greater absorption and desorption of moisture by sclerophyll fuels. The results also show that microclimatic differences in wind speed may be very important to determining differences in the potential flammability of rainforest, rainforest boundaries and sclerophyll forest. As mentioned, the boundary litter dried down very quickly during summer, but rates of fire spread never reach those of the sclerophyll forest, this is because wind speed is reduced by the boundary vegetation. Differences in wind speeds are probably also responsible for differences in flammability occurring during the extreme fire weather. While moisture contents are similar between the vegetation types on such days, the flammability of the sclerophyll forest is far above those of the rainforest and the boundary because it is windier.

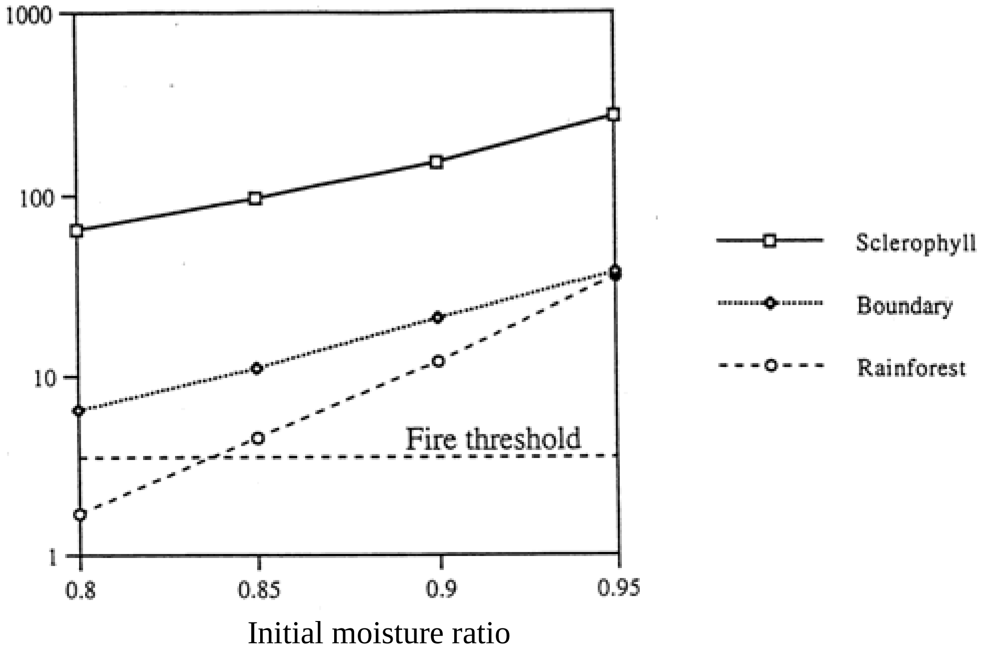


**Figure 7.2** Maximum rates of fire spread in each vegetation type on a day of extreme fire weather for various different initial moisture ratios.

## 7.2: General Discussion

The results from surveys, sampling and experimentation help identify the reasons why rainforest and rainforest boundaries are generally less flammable than sclerophyll forest. Microclimatic sampling showed that it is possible to characterise the microclimates in the different vegetation types and that rainforest is cooler during the day, more humid, less windy and darker than sclerophyll forest. Conditions in the boundary may vary, being more like the rainforest in some respects and more like the sclerophyll forest in others. This may be especially so where the boundary is wide and is composed of a matrix of rainforest and sclerophyll vegetation. Results from regression analyses of microclimatic data show that it is possible to predict differences in conditions between the vegetation types but that results may be influenced by site specific factors such as canopy gaps. It is not possible to accurately predict forest conditions from conditions at Kioloa in the short term, due to: the non-coincidence of external weather, daily hysteresis from differential delays in microclimatic response, the distance between Kioloa and forest stations and because of the sea breeze effect at Kioloa.

Microclimatic differences will lead to differences in the moisture content of fine fuels such as leaf litter (McArthur, 1967; Luke and McArthur, 1978; Cheney, 1981; Uhl and Kaufmann, 1990). Field sampling showed that there are differences between the moisture contents of fuels in the rainforest, the boundary and the sclerophyll forest (Chapter 3). Increases in fuel moisture content will lead to decreases in flammability (Pompe and Vines, 1966; McArthur, 1967; Luke and McArthur, 1978; Cheney, 1981; Vines, 1981). Microclimatic sampling has shown that there will be differences in fuel drying and fire spread between the different vegetation types studied. However, short term variation in the relationship between microclimates at different locations means that differences in rates of fuel drying and fire spread are hard to quantify. To examine how the vegetation will affect fuel drying and rates of fire spread it is necessary to study how microclimatic differences will influence fuel drying over time.

Surveying and experimentation also showed that there may be differences in the flammability of rainforest, rainforest boundaries and sclerophyll forest caused by structural differences in the live vegetation. The experimental burn (Chapter 5) showed that vines at low levels will extinguish fires because on all fences there were areas where the fresh vine remained unburned after the fire had consumed all the available surrounding fuel. It was shown that increases in the density of the vine lead to increases in the amount of vine that remained unburned. Results from structural surveys of the vegetation at the line of extinguishment of recent fires (Chapter 6) further supported the suppressive role of low level vines; it was shown that fires of high intensity may be extinguished where there is a high covering of vines at low levels.

Vines may have a suppressive effect on fire either because they reduce radiation transfer to adjacent fresh foliage or because they influence the speed of the wind. It is concluded that the suppressive effect of vines is due to their effect on the transfer of radiation. During the experimental burn the wind was blowing upslope against the fire, so that, as air passed over the fences to where the flames were, it would have eddied and drawn the flames closer to the fence. Had the wind been blowing with the direction of the fire it would still have directed the flames toward the fence. Although this has not been tested, it is probable that during the experimental burn, flames were directed toward the fence and therefore the effect of wind was minimised. Neither the results from the experimental burn nor the structural surveys were sufficiently detailed to allow development of an accurate vegetation suppression index. It is concluded, however, that rainforest boundaries may have reduced flammability due to the suppressive effects of vines. Results of the structural surveys suggest that the effect of the vine may be directly proportional to it's density.

Structural surveys and the experimental burn showed that there are differences in the flammability of rainforest and sclerophyll forest due to the nature of the understorey vegetation. During the experimental burn the most important factor governing the forward progress of the fire was the presence of monocot tussocks and associated dry litter. Structural surveys conducted along lines of fire extinguishment showed that intense fires will not go out where there are monocot tussocks or where leaf litter is deep. These results suggest that the presence of monocot tussocks will act to promote fire because they contribute directly to fuel loads and because they support and aerate leaf litter. This agrees with what has been reported in the past (McArthur, 1967; Howard, 1981). The importance of the sclerophyll understorey in promoting fire supports the conclusion that differences in the nature of the live vegetation will make rainforest and rainforest boundaries less flammable than sclerophyll forest.

The leaf flammability experiment (Chapter 4) showed that the ignitability of leaves is largely correlated with their leaf surface area, probably due to the physics of heating and cooling in leaves (Monteith, 1973).Rrainforest leaves were found to more flammable than sclerophyll leaves, perhaps purely because they are larger,. This result may also be an artifact of the experimental design, because leaves were placed horizontally in the muffle furnace. It would be useful to re-run the experiment, placing leaves in other orientations in the furnace. In other words, this result does not prove that rainforest or boundaries will be more flammable than sclerophyll forest during a bushfire, because conditions in the furnace may not represent the conditions of heating and combustion that occur during bushfires.

It is helpful to model the potential differences in flammability of rainforest and sclerophyll forest over increasing periods without rain. By modelling the decrease in litter moisture over time it was possible to investigate the cumulative effect of microclimatic differences on fuel drying and to highligh important differences in moisture relations. Boundary and sclerophyll fuels absorb more moisture at night but lose more moisture during the day than rainforest fuels. This is because fuels in the boundary and the sclerophyll forest are more influenced by external changes in temperature and humidity. Differences in the daily absorption and desorption of moisture by fuels leads to differences in fuel drying after rain: fuel in rainforest dries more slowly than that in the other vegetation types. These predictions are dependant upon the accuracy of the litter moisture model. Calibration showed that there may be problems optimising the drying constant and canopy cover terms when more than one site is used or litter is not collected at the precise point where microclimatic samples are taken. Despite this, it has been shown that the model can be optimised in order to study general differences in fuel drying between vegetation with differing canopy densities and microclimatic conditions.

It is also instructive to model changes in flammability from microclimatic data. Modelling allows examination of changes in flammability over extended periods without rain and during periods of extreme fire weather. In this study fire modelling has shown that there are clear differences in the flammability of rainforest and sclerophyll forest especially during extreme fire weather or prolonged periods without rain. Under certain conditions rainforest and rainforest boundaries will be flammable. The results show that there are both long and short term differences in the flammability of rainforest: long term differences result from the effects of microclimate on fuel drying; short term differences result from the direct effects of microclimatic parameters eg. wind speed on fire behaviour. This study has shown that rainforest will only become flammable under extreme fire weather and fuel dryness conditions.

This study confirms previous reports that the distribution of rainforest and the position and widths of rainforest boundaries may be quite stable after a single fire (Stocker, 1981; Stocker and Mott, 1981; Unwin *et al,* 1985, Unwin, 1989). Even high intensity fires may be extinguished in rainforest, and tree species common to rainforest boundaries and mixed forest coppice well after fire. There is also evidence that supports the theory that increasing the frequency of fire may impact upon rainforest distributions and the nature of boundaries (Webb and Tracey, 1981a,b; Unwin *et al,* 1985; Ash, 1988; Unwin, 1989; Adam, 1994). It has been shown that fire will burn into boundaries and rainforest when fuel moisture is low and this means that fire may penetrate to impact upon fire sensitive rainforest trees. Surveys of the damage done to trees by fire showed that rainforest/boundary species are more vulnerable to being killed by fire when they are very small; as suggested in the literature (Stocker, 1981; Stocker and Mott, 1981; Ash, 1988). Infrequent fires of high intensity may not impact on rainforest distribution, because rainforest is able to recolonise in the fire interval. Frequent fires of low to moderate intensity will impact upon the rainforest boundary and, ultimately, the rainforest. This has important implications for the management of fire in mixed vegetation, because the increasing frequency of fires of all intensities due to ignition by humans will probably affect the width of rainforest boundaries and may deplete rainforest. The effect of different fire regimes on the distribution of rainforest and rainforest boundaries could be studied by using the same procedures to develop topographic models of the behaviour of fire in the different vegetation types.

The findings of this study are also important in terms of controlling and preventing bushfires and minimising the damage they cause. It has been shown that litter moisture models can be used to determine fuel drying in areas with differing canopy cover and from this potential flammability can be determined. Canopy cover is very important to determining litter moisture and flammability. Hence any canopy destruction in rainforest will increase flammability. This has been demonstrated in the tropics, where it is observed that rainforest may burn after cyclone damage to the canopy (Unwin, *et al,* 1985; Unwin, 1989). Similarly, in rainforest with a canopy reduced by logging or clearing, flammabilities will be increased, as found with some of the rainforest fires that occurred in Indonesia during 1997. Because a general model of fire behaviour has been developed, this approach can be applied to assess the potential flammabilities of disturbed rainforest.

Models that incorporate canopy effects on litter drying and ultimately fire spread will also be useful for developing spatial models of fire movement in a landscape composed of different vegetation types. Predictive models have been an important part of the study and prevention of bushfires for the last 30 years (McArthur, 1967; Luke and McArthur, 1978; Cheney, 1981;

Whelan, 1995). Predictive models incorporating the effects of different vegetation types will allow more efficient assessment of fire risk when controlling bushfires, or when preventing their occurrence through hazard reduction burning. The more efficient assessment of bushfire risk will lead to the more efficient deployment of personal and equipment for fire management and control. This study has also indicated that vines may act to halt the spread of fire, the identification of fire retardant vegetation that can be used for the protection of property and life has been an important focus for research (Vines, 1981; Gill and Moore, 1996). The results of this study suggest that vines may reduce fire spread by reducing radiation transfer during fire, this result is well worth further investigation.

In summary, the major findings of this study have been:

- Microclimatic conditions differ between the different vegetation types studied. Rainforest is cooler during the day, more humid, less windy and darker than sclerophyll forest. Conditions at the boundary will vary between sites.
- Microclimatic differences and differences in canopy cover will affect the rate of fuel drying in the different vegetation types. Fuel in rainforest dries more slowly than fuel in sclerophyll forest.
- Predictive models can be used to determine differences in moisture content and differences in the flammability of different vegetation types.
- The nature of the live vegetation in rainforest and rainforest boundaries will make these vegetation types less flammable than sclerophyll forest. This is due to a suppressive effect of vines that are common to rainforest and due to the promotion of fires by the sclerophyll understorey.
- Analysis of the factors that operate to suppress fires in rainforest has lead to insights about the role of fire in determining the relative position of rainforest and sclerophyll forest. The study has shown that under certain fire regimes the distribution of rainforest may be adversely affected by fire.
- The approach used in the study may be used in the future for preventing or controlling bushfires and minimising the damage they do.

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# Appendix 1

## Equation to predict evaporation, after Penman in Brutsaert (1982)

$$E = Q\left(\frac{\Delta}{\Delta + \gamma}\right) + E_a\left(\frac{\gamma}{\gamma + \Delta}\right)$$

where,

$E$ = Potential evaporation, mm $s^{-1}$

$$Q = \frac{Q_n}{10^6 L_e}$$

$Q_n = Q_s(1-a)+Q_{ld}-Q_{lu}$ $Qn\ =\ (^{1}\ \ ^{a})\ +\ Qld\ \ Q1u$

$Q_s = 2.261R$

$R$= PAR, mV on ANU sensor = 0.8845 $Wm^{-2}$

$a$= Albedo = 0.18

$Q_{ld} = 0.000000056697\varepsilon t_a^4 cc_v^2$

$\varepsilon = 0.51 + 0.066e_a^{0.5}$

$t_a$= Air temperature, °$K$

c= 0.1 + $0.0025C_{\%}$

$C_{\%}$ = Canopy cover, %

$c_v = 1-(1-0.01C_{\%})(1-0.01c_l)$

$c_l$ = Cloud cover, %

$Q_{lu} = 0.000000055273t^4$

t=Surface temperature, °$K$

$L_e = 2.5 - 0.00237(t_a - 273.16)$

$E_a = 0.00000301(1 + 0.54U)(e^* - e_a)$

$U$= Wind speed at 2m, $ms^{-1}$

$e^* = 6984.505294 + t_a(-188.903931 + t_a(2.133357675 + t_a(-0.01288580973 + t_a(0.00004393587233 + t_a(-0.00000008023923082 + 6.13820929e^{-11t_a})))))$

$e_a = 0.01He^*$

$H$ = Relative humidity, %

$$\Delta = \frac{373.15e^*}{t_a^2}\left(13.3185 - 3.952t_r - 1.9335t_r^2 - 0.5196t_r^3\right)$$

$t_r = 1 - 0.002679t_a$

$\gamma = 0.67$