The characteristics and accumulation of surface fine fuel in the eucalypt forests and woodlands of Redland Shire, Queensland

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Statement of Originality

The material presented in this thesis has not been previously submitted for a degree or diploma in any university, and to the best of my knowledge contains no material previously published or written by another person except where due acknowledgement is made to the thesis itself.

Jan Gilroy

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Abstract

Fires, whether wild or prescribed, exhibit a dominating influence on the Australian landscape. Land managers are required to develop and implement fire management plans in order to contend with the complex requirements of life and property protection as well as the ecological needs of the fire-adapted landscape. Land managers in southeast Queensland rely upon fuel growth models and hazard assessment guides developed in other regions of Australia and the reliability of these guides has not been thoroughly tested.

Fuel accumulation models are used to estimate and predict fuel quantities worldwide. The non-linear model predicting surface fine fuel load in the *Eucalyptus racemosa* open woodland is y = (61.976)*(1-1/((1.00496)**(x+(41.5212))))*((61.976)>0)*((1.00496)>1). For the *Eucalyptus major/Corymbia citriodora* open forest, non-linear estimation was not able to provide a reliable fuel-growth curve due to the absence of available sites.

The linear regression model suggests that time since fire, fuel depth and foliage projective cover are reliable predictors of surface fine fuel quantity and they can independently explain a total of 68% of the variation within the data set. The most reliable model for *E. racemosa* open woodland was y = (0.286)Fuel Depth + (0.321)Time Since Fire + (0.100)Foliage Projective Cover. The variation in the data also suggests that fuel is related to other factors other than those measured here.

The examination of the efficacy and accuracy of the use of the Overall Fuel Hazard Guide, revealed that a highly significant underestimation in both the minimum and maximum surface fine fuels as determined by the Overall Fuel Hazard Guide, in both *E. racemosa* open woodlands and *E. major/C. citriodora* open forest. Whilst the Overall Fuel Hazard Guide provides a good indicator of contributors to the overall fuel load, caution should be used due to the consistent underestimation of the actual surface fuel loads.

Leaves remained the major component of the fuel load (8.49±1.21 t/ha) over this time frame, reaching equilibrium approximately 7-8 years post-fire. The bark (2.38±0.46 t/ha) and twig (6.85±2.02 t/ha) components showed no useful trends over this timeframe. From an

operational perspective, this result shows that land managers do not need to drastically alter their prescribed burning regimes due to changes in the composition of the fuel load.

Terminology

Ecological burning
The treatment of vegetation in nominated areas by the use of fire to achieve specific ecological/conservation objectives.

Fire behaviour
The manner in which a fire reacts to variations in fuel, weather and topography. Common measures of fire behaviour are ‘rate of spread’, ‘flame height’, fire spotting distance’ and ‘intensity’.

Fire ecology
The study of the inter relationships between fire and the biota.

Fire Frequency
The time interval between successive fires at a particular site or over a particular area or vegetation type.

Fire Intensity
The heat (measured in kilowatts) released per meter of the fire front. Generally classified as low (<500kWm^{-1}), moderate (500-3000kWm^{-1}), high (3000-7000kWm^{-1}) or very high (7000-70 000kWm^{-1}).

Fire Regime
The combination of season, intensity, frequency and scale of fire in a given area over a period of time.

Hazard reduction
The planned use of fire to reduce fuel loads in a specified area.

Prescribed burning
The controlled application of fire under specified environmental conditions to a predetermined area and at the time, intensity and rate of spread required to attain planned resource management object

Wildfire
An unplanned grass, scrub or forest fire.

(Adapted from the Interim Guidelines and Procedures for Ecological Burning on Public Land in Victoria, DNRE 1999)

Chapter 1. General Introduction

1.1 Background

Fire is an inseparable part of the Australian landscape (Whelan 1995). Consequently, fire continues to play an important role in shaping the environment (Catchpole 2002, Bowman 2003, Ellis *et al*. 2004). The influence of fire can lead to positive effects on biodiversity by creating mosaics within the landscape and providing variability (both temporally and spatially) within the landscape, creating habitats for a variety of fauna species for example, through the formation of tree hollows and thereby promoting biodiversity (Walker 1981). Conversely, fire effects can also lead to negative biodiversity impacts on the landscape by: causing localised extinction of species, the destruction of tree-hollows and an oversimplification of vegetation stands (Gill & Williams 1996, Bradstock *et al.* 1998, Gill 2001).

There is an increase in the risk that fire poses to property, built and natural assets and, of course, lives as more people move into the urban bushland interface. As a result of the devastating bushfires like those dating back to Victoria (1939), Hobart (1967), Sydney (1994), ACT and northern Victorian Highlands (2003) and most recently in the Eyre Peninsula, South Australia (2005), fire management is an essential, and very public requirement for all levels of land management from local to federal (Gill & Williams 1996, McCarthy 1996).

Effective and sustainable fire management incorporates a number of factors. Hazard reduction to reduce fuel loads is one method that is the commonly used among land management agencies in Australia (Conroy 1993). The purposeful application of fire in the landscape affects one key aspect, the fire regime. Fire frequency, intensity, seasonality, and extent are features comprising the fire regime (Gill 2001). These aspects are all interrelated and need to be considered when developing an effective fire management plan (McCarthy *et al.* 1999). From these characteristics of fire regime, fire frequency is the only aspect that can be realistically managed (Collett & Neumann 2003). However, the timing (seasonality) and to a lesser degree, fire extent (area burnt) may also be manipulated artificially by land managers (Conroy 1993). Pre and post-fire monitoring of bushfire events over a period of time in the landscape has become an essential part of a land manager's role and responsibility to

effectively reduce the risks of fire to lives and the built environment whilst maintaining the biodiversity requirements of the landscape. This requires an intricate knowledge of firstly, the effects of fire on the flora and fauna present in the landscape and secondly, the accumulation of fuel within an ecosystem (Fogarty 1993).

It is important to acknowledge that the Council of the Australian Government (COAG) National Inquiry in Bushfire Management and Mitigation, set up following the conflagrations in the Australian Capital Territory and northern Victoria in 2003, has recently recognised and recommended that emphasis be placed in the area of fuel dynamics research (Ellis *et al*. 2004). Fuel traits can directly affect fire behaviour and as such, are essential to understand and manage (Conroy 1993). An extensive knowledge of the fuel dynamics within a region allows land managers to predict fire behaviour more accurately and assess bushfire hazard (Ellis *et al*. 2004). The southeast Queensland region lacks fundamental knowledge and assessment of potential fuel hazard and fuel accumulation dynamics in the most represented ecosystems with current research efforts placed in endangered and threatened ecosystems, which often represent smaller areas of land separated from the urban-bushland interface.

1.2 The role of fire in the landscape

1.2.1 Fire & Eucalyptus Vegetation

In Australia, over 80% of remnant eucalypt forests have either been cleared or modified, with half of the remaining area of forest located within conservation reserves that have previously been logged or subject to human disturbance (Norton 1996, Gill & Williams 1996). There are numerous patches of remnant vegetation located on local council land, in National Parks, state forest and private property that require additional vegetation protection in order to retain the remaining native vegetation for conservation purposes (Roberts 1990). Eucalypt forests are biologically diverse and it is essential to ensure proper management of this unique and endemic forest ecosystem (Norton 1996). Detrimental fire regimes have already been associated with species declines, such as the black-breasted button-quail (*Turnix melanogaster*), is an example in southeast Queensland where fire exclusion is recommended on order to maintain sufficient litter understorey cover for this species' behavioural habits (Woinarski 1999). Species specific fire management plans have been developed for a number of threatened taxa throughout Australia (House 1995). The use and impact of fire is now

accounted for in most management plans, for both mitigation of the risk and for biodiversity conservation (Gill & Williams 1996).

All eucalypt communities in Australia will at some stage encounter fire (Gill 1997). It is the intensity, frequency, season and extent that will differ (Luke & McArthur 1978). Some species of eucalypts are dependent on fire for regeneration and survival whilst others require exclusion from fire to survive (Gill 1997). In southeast Queensland, it was observed that the growth response of *Eucalyptus drepanophylla* and *E. acmeniodes* were not affected by frequent annual burning (Guinto *et al.* 1999). However, *E. tereticornis* and juvenile *Corymbia intermedia* responded positively to annual burning while the larger, more mature individuals of *C. intermedia* appeared to respond negatively (Guinto *et al.* 1999). It is these and similar species that are most susceptible to the higher frequency of fire, as they require adequate time between fires to reach reproductive maturity and restock seed banks (Gill 1997). It is difficult to assess these relationships effectively without acknowledging the effects of disturbances such as herbivory and weather extremes on their life cycle (Gill 1997, Smith *et al*. 2004). It is this type of fire frequency that is usually adopted by land management agencies for hazard reduction purposes. Recent studies (Gill & Williams 1996, Smith *et al*. 2004) have revealed that in some cases frequent fire can result in the decrease in biodiversity due to an oversimplification of the vegetation structure and the causal effect of localized extinction for both floral and faunal species.

It is now recognized that a variable fire frequency both temporally and spatially is the optimum approach for species diversity maintenance and a reduction in the severity of unplanned fires (Gill & Williams 1996, Bradstock *et al.* 1998, Fernandes & Botelho 2003). Diversifying the age structure of a vegetation community, can mitigate the risks that are associated with monocultures such as reduced biodiversity and localized extinction (DNRE 1999). Southeast Queensland has been recognized as a biodiversity ‘hotspot’ (Ellis *et al.* 2004). This has major implications for fire management and for further peri-urban development to accommodate an increasing population.

1.2.2 Fire & the Urban-bushland Interface

The southeast Queensland region has become the most sought after residential locality in Australia with a dramatic population increase over the past 10 years leading to major

residential development particularly near the ranges (Sattler & Williams 1999). As a direct result of unsuitable planning and increasing fragmentation of the landscape, a marked decline of many of coastal southeast Queensland's vegetation ecosystems has occurred, increasing the number of rare or threatened taxa (Sattler & Williams 1999). Remnant vegetation, under either local or state jurisdiction is thus now bordered by suburbia, industry and agriculture. This increase in fragmentation of the landscape has two main effects; (1) the remnant ecosystems are areas of high biodiversity; and (2) these areas can potentially pose a significant bushfire risk to the residents (Simmons & Adams 1986).

Fire and potential fire impacts are undoubtedly of major concern to those that live near these remnant patches of bushland, which is more commonly termed the 'urban interface' (Bradstock & Gill 2001). At the urban interface, fragments of bushland are subject to frequent planned burns to protect surrounding property and assets (Bradstock & Gill 2001). A reduction in the ground fuels permits land management agencies to actively suppress wildfires or perform other fire management activities to reduce potential risks. This more frequent application of fire to reduce hazard can lead to many of the conservation problems discussed earlier. The dilemma for the land management agencies is how to balance the obligation to manage the fuels with the requirements for the taxa contained within the bushland areas (Whelan 2002). The frequency of fires may be exacerbated by the increased risk of ignition associated with events such as arson and dumped garden vegetation, that are increasingly a problem as the of the urban interface increases (Bradstock & Gill 2001).

1.3 Fire Behaviour

The primary objective of hazard reduction is to reduce the amount and composition of ground fuels (Anderson 1982, McCarthy 1996). The amount of fuel in addition to the topography and climate are key factors that influence the fire behaviour (Catchpole 2002). However, to describe fire behaviour a number of other processes need to be understood, including those of ignition and combustion. The process of setting fuel on fire is termed ignition (Tolhurst & Cheney 1999). This is supported by the process of fuel oxidation or combustion where fuel is consumed and energy is released as heat (Tolhurst & Cheney 1999). Some sources of ignition include lightning, spontaneous combustion and arson (Bradstock *et al*. 1998, Whelan 2002).

In extreme conditions (e.g. drought, high temperatures and winds, low relative humidity) it is the prevailing weather conditions that can ultimately determine a fire's behaviour regardless of the amount and type of fuel and topography (Bradstock & Gill 2001, Salvador *et al.* 2005). For example, an increase in the wind speed can amplify the combustion rate and behaviour by providing more oxygen and forcing the flames towards the fuel bed (Luke & McArthur 1978). Wind driven fires are commonly associated with large conflagrations in the landscape and severe crown fires (Tolhurst & Cheney 1999, Keely & Fotheringham 2001). However, as these extreme conditions are uncommon, fuel is regarded as the more frequent contributor to fire behaviour in ordinary weather conditions.

1.3.1 Fire Characteristics

Fire growth, flame characteristics, fire shape, rate of spread, spotting, heat output, intensity and junction zones are all parameters of fire behaviour (Tolhurst & Cheney 1999). Some of these characteristics are fuel dependent and will be discussed further. Fire growth is the development of a fire and the speed at which it spreads (Cheney 1981). It is determined predominantly by two main factors: (1) the ignition and combustion processes, and (2) through the heat transfer process i.e. convection, which both influence the direction in which a fire spreads (Tolhurst & Cheney 1999). The flame characteristics are directly related to the composition of the fuel and are defined by flame height, length, depth, residence time and burnout time with each being fuel-dependent (Luke & McArthur 1978). These characteristics will also affect the rate at which fire spreads from point to the next (Anderson 1987).

Many of the models developed to predict fire behaviour assume a direct relationship between rates of spread and fuel quantity (Raison *et al*. 1983, Buckley 1992, McCarthy *et al*. 2001, Sandberg *et al*. 2001, Fernandes & Botelho 2003). However, in some Australian eucalypt forests, for example the Jarrah forests of Western Australia, both quantity and layers of fuel vary both spatially and temporally, and in some cases quite dramatically (Burrows 2001). Therefore the models based on these properties may, in some locations, appropriately explain vegetation types, however used elsewhere, as demonstrated in Western Australia; the models may mask certain effects, other than those properties, that can also affect the fire behaviour. A more comprehensive knowledge of the fuel characteristics especially in relation to the movement of fire is needed.

1.3.2 Spotting

Spotting occurs where firebrands (generated mainly from bark, but can be any airborne vegetative material) are carried by winds and can start new fires forward of the main fire front (Tolhurst & Cheney 1999). The probability of more extreme fire behaviour occurring such as spotting, depends on the type, amount and moisture content of appropriate fuel available (McCarthy 1996). This is also affected by the amount of time that has past since the previous fire (Whelan 1995). It is likely that higher quantities of fuel will be available to generate firebrands the more time that has past (Tolhurst & Cheney 1999). The bark of many eucalypt species such as stringybarks can form firebrands even in relatively mild conditions due to the flaky fragments of bark (Fernandes & Botelho 2003). These fragments can be carried long distances, sometimes up to 30 km ahead of a fire depending on weather conditions (Wilson 1992). An example of spotting behaviour are the gum-barked eucalypts (e.g. *E. regnans* in Victoria and *E. oreades* locally in southeast Queensland) that have long ribbons of bark that can be carried tens of kilometers forward of the fire front (Tolhurst & Cheney 1999). In an extreme case, spotting was measured up to 30 kilometers away in the bushfires that occurred in the northern Brisbane areas around Beerburrum, Queensland (in 1998) with fires starting on Moreton Bay Island as a result of firebrands from the mainland (Gourley, DPI Forestry pers.comm. 2005).

Spotting makes suppression efforts very difficult, sometimes impossible, contributing to the failure of many first-attack responses to suppress bushfires (Anderson 1982, Wilson 1992, McCarthy 1996). Prescribed burning and research into fuel dynamics can help to predict and reduce this type of fire behaviour and increase the success of suppression efforts as shown in Victorian studies of eucalypt forests (McCarthy & Tolhurst 2001, Fernandes & Botelho 2003).

1.3.3 Fire intensity

Finally, fire intensity is also dependent on fuel composition and is an important predictor of fire behaviour and suppression difficulty (Catchpole 2002). This relationship was mathematically described by Byram (1959) and is defined by the following equation (Wilson 1992);

$$I = H.\ W.\ R$$

Where:

I = fireline intensity

H = heat content of fuel (kJ/kg)

W = weight of fuel burnt per unit area (kg/m^2)

R = rate of fire spread (m/s)

Fire intensity has been described as the function of the amount of fuel burnt in the flaming front of a fire, taking into account the fuel moisture content and the rate of spread of the fire (Tolhurst & Cheney 1999). In eucalypt communities, rates of spread can vary from fractions of meters per minute to a few meters per second with intensities reaching 100 000 kW m^{-1} (Gill 1997). These intensities are more likely to occur in large dry fuel beds, on steep slopes during strong winds (Gill 1997). Low intensity fires generally do not kill overstorey species but consume the (available) dead fuel (dead grasses, shrubs and graminoids) (Catchpole 2002). Moderately intense fires have the ability to kill shrub and tree species but generally do not consume them, as opposed to fires of high intensity that are capable of removing all of the available fuel - both alive and dead (Catchpole 2002).

Intensity is a difficult parameter to quantify and studies have found that intensity models become very specific for both site characteristics and weather conditions on the particular day (Chatto 1996, Brookes *et al.* 2004). Therefore, fire intensity models that have been developed for one fuel type should not be applied to other fuel types, especially those that are structurally different.

1.4 Fuel

Fuel consists of live and dead vegetation that can include leaves, twigs, bark, flowers and fruit (Simmons & Adams 1986, McCarthy *et al.* 1999). Fuel is the most important factor that contributes to any fire that can be effectively ‘controlled’ or managed by land managers (McCarthy *et al.* 2001, Brandis & Jacobson 2003, Fernandes & Botelho 2003). The major contributor to surface fuels and fire behaviour in most Australian forest and woodland communities are eucalypts (Gill 1997). Quantifying the composition and characteristics of fuel in these communities (ideally from site to site), is critical for accurate assessment, especially in southeast Queensland, where research is lacking on this topic.

The fuel load and site characteristics largely determine the behaviour of a fire and namely the likelihood of ignition (through the size and arrangement), how fast a fire will spread (due to

horizontal continuity) and the intensity of the fire (via moisture content and presence and volatiles e.g. oils) (Anderson 1982).

The manipulation of fuel in bushland areas has two main functions; (1) for ecological purposes, to protect and conserve biodiversity both temporally and spatially from inappropriate prescribed burning and potential invasion from exotic species (Gill & Williams 1996), and (2) to reduce the probability of fire occurring and protect adjoining property and assets that principally occur at the urban bushland interface (Bradstock *et al.* 1998, Sandberg *et al.* 2001). The need to reduce the fuel load is especially vital at the urban bushland interface where the loss of property and possibly human life is a real, everyday threat. The fires that encroached into the suburbs of Canberra in January of 2003 are a lasting reminder of the vulnerability of these residential areas. Greater awareness and concern of this issue is developing within communities that are concerned with conservation on their properties and remaining natural bushland (Bradstock *et al.* 1998).

1.4.1 What influences fuel quantity?

It is widely acknowledged that the fuel loads are dependent on the type of vegetation, the time since the last fire, rainfall and the amount of biomass present (Walker 1981, Brandis & Jacobson 2003). Differing rates of decomposition and accumulation over time will also affect the quantity and components of surface fuels (Fox *et al*. 1979, Simmons & Adams 1986).

There will be differences in the amount of litterfall due to season and it has been suggested that litterfall, for eucalypt dominated forests in southeast Queensland, northern New South Wales and South Australia, are at their highest between August–February and slowest during the cooler winter months (Birk 1979, Pressland 1982, Hutson 1985). The average annual rainfall can also affect forest productivity, which in turn affects litterfall, and subsequently fuel load (Fox *et al*. 1979, Anderson 1982). Fuel quantity will also be affected by the topography and geology of the surrounding area including aspect, slope and soil type (Chatto 1996).

1.4.2 Fuel & Fire Behaviour

Fuels can also differ within the same vegetation type due to climatic, topographical features, productivity and years since the last fire event (Brookes *et al.* 2004). The continuity of fuel

refers to the distribution of fuel both horizontally and vertically and partly controls where a fire will travel to and how fast it will do this (Anderson & Brown 1987). Forest fuels may be patchy and discontinuous in one area, while fuel in other areas can be compacted and continuous, both within the same vegetation type (Catchpole 2002). These examples play a vital role in influencing the fire behaviour and pattern of fire spread (Millar & Urban 2000, Catchpole 2002). Miller & Urban (2000) investigated the connectivity of fuels in forests and its affects on surface fire regimes. They found that connectivity in a particular area was '*a function of fuel loads, fuel moisture and fuel bed bulk density*' (Millar & Urban 2000). Furthermore, fuel beds varied both spatially and temporally in a single vegetation type depending on the number, size and species of trees present (Millar & Urban 2000).

The behaviour of fire will incorporate the small scale variations in fuel continuity and spread much further when compared with low hazard conditions where 'bare' areas may act as a barrier to contain fire (Catchpole 2002). Due to these factors, it is unlikely that taking only one or a small number of samples will provide a representative estimate for the total area (Tolhurst & Cheney 1999). Tolhurst & Cheney (1999), Chatto (1996) and Fogarty (1993), support the notion that fuel loads are useful predictors of fire behaviour, only when measured over a range of fuel ages.

The vegetative profile can be used to classify fuels (Figure 1). Though '*total*' fuel is the combination of all live and dead combustible material from the canopy to the decomposed organic material on the ground it comprises the entire vertical and horizontal vegetative profile (Tolhurst & Cheney 1999). Fine fuels are those which are the first type of fuels to be consumed/ignited in a fire and are the largest contributor to total fuel quantity and fire behaviour (Walker 1981). Fine fuels consist mainly of leaves and small twigs (usually less than 6 mm) (Cheney 1981). This can be linked to fire intensity where low, moderate and high intensity fires will consume all fine fuels that are available, whereas larger fuels, generally greater than 6 millimeters, require the higher intensity fires to ignite and be consumed (Whelan 1995). To further emphasise this importance, fine fuels are also part of the entire vegetative profile and may provide a pathway for fire into the overstorey (Burrows 2001, Buckley 1992*a*).

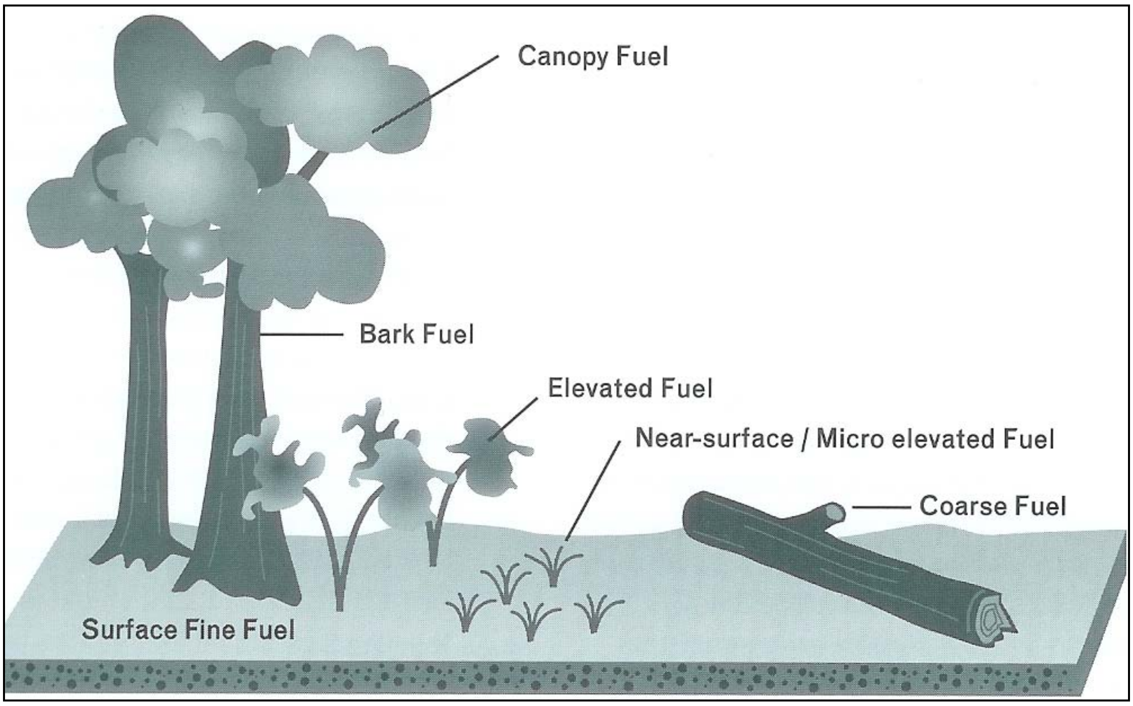

Figure 1.1 Different components of fuel in a typical woodland (Reproduced from Tolhurst & Cheney 1999).

Individually, 'surface fine fuels' are those on the surface of the ground. Comprising the majority of the fuel weight proportion and consisting of all live and dead material from the overstorey and understorey that is less than 6 millimeters in thickness (dead material) and less than 2 millimeters (live material) (Just 1977, Simmons & Adams 1986). Fire behaviour, (i.e. the flame height, rate of spread and intensity) is directly affected by the size and arrangement of surface fine fuels (Conroy 1993, Brookes *et al.* 2004).

'Near surface fine fuels' are the low shrubs, grass tussocks, sedges and suspended dead matter up to 0.5 m that are not in contact with the soil surface (Tolhurst & Cheney 1999). The presence of this type of fuel can increase the fuel hazard greatly due to distribution, aeration and faster drying times allowing greater continuity and potential for fires to 'climb' or ladder to higher levels, potentially into the crown (Catchpole 2002).

Elevated fuels consist of shrubs, heath and suspended dead material up to 1.5 m above ground (McCarthy *et al.* 1999). Elevated fuel can contribute significantly to fire behaviour depending on the size of the foliage and chemical composition (Chatto 1996). The ignitability of elevated fuels can additionally determine flame height, spread to canopy and affect horizontal and vertical spread (Fernandes & Botelho 2003).

Similar to elevated fuels, bark can also contribute to the spread of fire by providing a ladder between the surface and overstorey and also through the formation of firebrands that can, under suitable weather conditions, create spot fires (Chatto 1996). This type of fuel is strongly influenced by the plant species present at any particular site (Luke & McArthur 1978). For example, the bark of some Victorian eucalypt species, *E. globoidea and E. consideniana*, is loosely held and is sufficient to cause considerable spotting behaviour even in lower intensity fires (Buckley 1992*a*). While another Victorian eucalypt species, *E. macrorhyncha*, has bark threads that are retained and form a fibrous layer that increases with age and may also contribute towards spotting (Crockford & Richardson 1998).

Finally, canopy fuels are the live leaves and twigs of the overstorey and will only burn under the most intense and severe conditions (Tolhurst & Cheney 1999).

This study will focus only on the surface fine fuels, as this fuel type is ignited and consumed first in the fire front, and has been demonstrated to be the strongest contributing factor to the development and movement of bushfires in Australia (Luke & McArthur 1978, Raison *et al.* 1983, Buckley 1992*b*, Catchpole 2002). All fires begin at some point in the surface fine fuels and is therefore, the most essential characteristic to quantify accurately and precisely for a particular region.

1.5 Objectives & Aims

The use of hazard reduction through prescribed burning is the most commonly applied land management method used to manipulate vegetative fuel loads for property protection or for ecological purposes (Conroy 1993, Bradstock & Gill 2001, Brandis & Jacobson 2003). The problem for land management is how to balance these potentially conflicting objectives. An adaptive management approach is needed to incorporate new information into existing frameworks as it arises. Land managers need to have a good understanding of the variables that will affect a fire within a particular area, as well as understanding the longer term impact of this type of fire regime. Understanding the quantification of fuel is a major objective of this type of land management.

To further complicate this, eucalypts can vary greatly in the production, accumulation and decomposition of fuel, not only between individual species but also between different locations, depending on soil type and topographical features (Birk 1979). Given the widespread use of the Overall Fuel Hazard Guide in southeast Queensland and the different eucalypt species in this region, this study aims to gain an understanding of the fuel accumulation potential in the Redland Shire region of southeast Queensland and provide a critical assessment of the accuracy and precision of the Overall Fuel Hazard Guide. An assessment of the types of fuel (leaf, twig and bark matter) that contribute to surface fine fuel load will be undertaken to gain some understanding of the accumulation potential of each component over time.

Consequently, the specific aims if this study were;

1. To investigate surface fine fuel accumulation over time within two vegetation types,
2. Compare the estimated with that of the actual surface fine fuel load, and
3. To investigate how the proportion of individual surface fine fuel components change over time.

Chapter 2. Study area and general methods

2.1 Study area

Redland Shire consists of three distinctive regions, the mainland, southern Moreton Bay Islands and North Stradbroke Island. It is bordered by the Pacific Ocean to the east, the city of Brisbane to the north and west and Logan City to the south. The mainland area consists of extant vegetation communities that are mostly open forests or woodlands with occasional closed forests and wetlands (LAMR 2001). The islands are dominated by wetlands and heath communities (LAMR 2001).

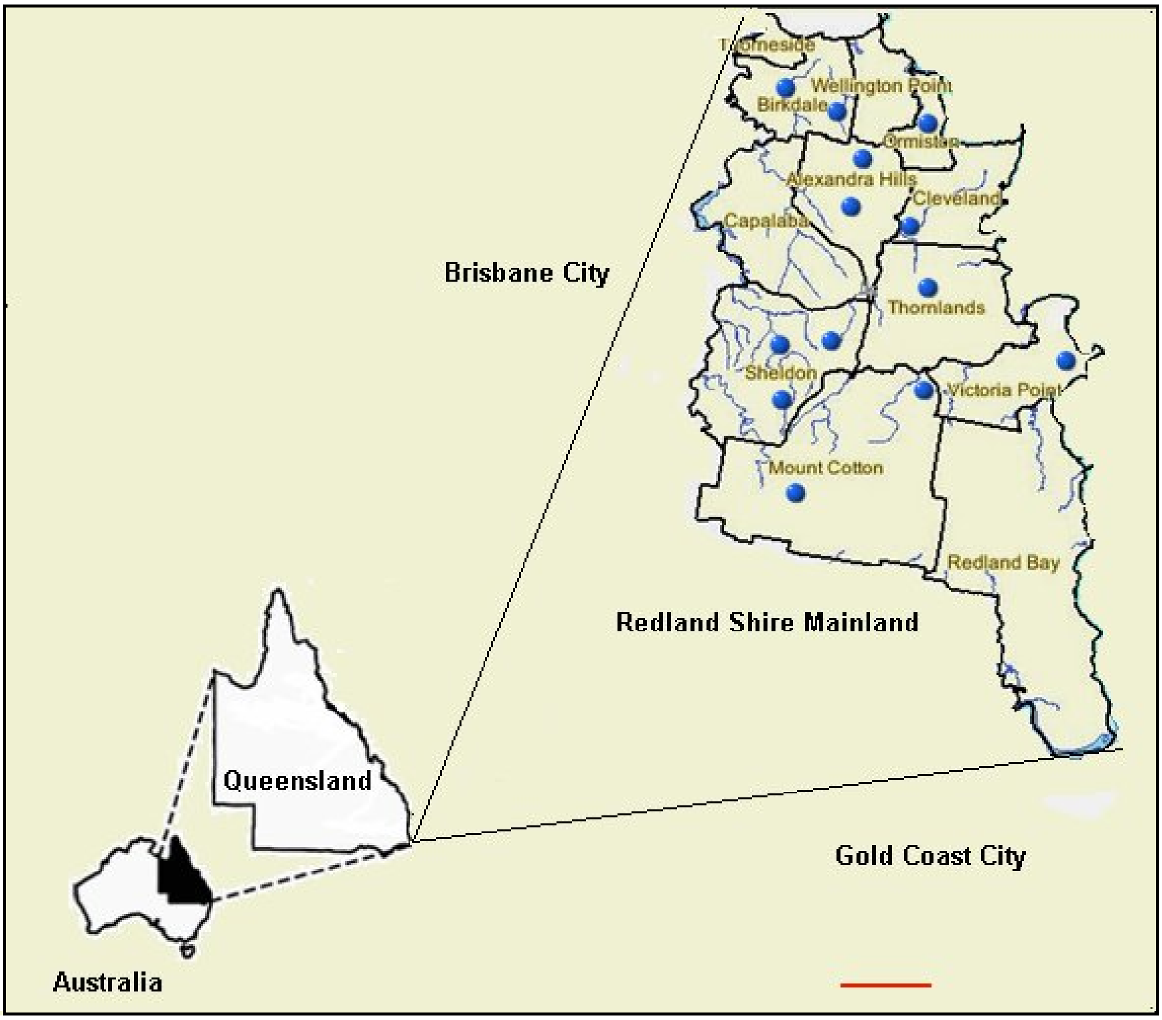

Figure 2.1 Locality map of Redland Shire in relation to Queensland and Australia. Dots indicate sites used in the present study.

Historical land uses of the Redland Shire were mostly agricultural including cotton growers and sugar plantations (RSC 2005). These practices were eventually replaced by fruit crops

(RSC 2005). Current land use is mostly residential, but is not limited to and includes agricultural and mining activities (RSC 2005).

2.2 Climate

The Redland Shire experiences a sub-tropical climate, with temperatures ranging from 11-28 degrees Celsius for most of the year (BOM 2005, RSC 2005). The mean rainfall for the area is 1322 mm, with the October-April season being wetter than that of May-September (BOM 2005). Prevailing winds generally come from the south-east (RSC 2005). Fieldwork was conducted in the study area was between March and September 2005.

2.3 Study species

This study was undertaken in the *Eucalyptus major/Corymbia citriodora* open forests and *Eucalyptus racemosa* open woodlands of mainland Redland Shire. Ranging from Thorneside to the north, Sheldon to the west, Wellington Point, Victoria Point and Cleveland on the eastern coastline with Redland Bay and Mount Cotton in the south and covers approximately 540 km^2 (Figure 2.0).

The two major vegetation types examined in this study are;

2.3.1 *Eucalyptus major/ Corymbia citriodora* open forest

This vegetation type occur on soils of red-yellow podzolics on low hills of metasediments (LAMR 2001). Open forest is defined by the foliage projective cover (30-60%) and the life form and height of the tallest stratum (Trees 10-30 m) (Specht *et al.* 1974).

Occupying 1744 ha of undulating country in the west, this vegetation type was dominated by *Eucalyptus major* and *Corymbia citriodora* with associations with individuals of *E. fibrosa*, *E. microcorys*, *E. resinifera*, *E. seeana*, and *E. siderophloia* (LAMR 2001). In the grassy understorey, the flora species consisted of predominantly *Cymbopogon refractus*, *Ottochloa gracillima* and *Themeda triandra* (LAMR 2001). Shrubby understoreys were also evident and consisted of *Acacia spp.*, *Pultanea spp*. *Leptospermum polygalyfolium*, *Jacksonia scoparia* and *Westringia eremicola* (LAMR 2001).

2.3.2 *Eucalyptus racemosa* open woodland

This vegetation type occur on red-yellow podzolics on low hills of sedimentary rocks and metasedimentary substrates and covered 1450 ha of the study area (LAMR 2001). *Eucalyptus racemosa* predominates these communities with occasional individuals of *E. fibrosa*, *E microcorys*, *E. seeana*, *E. siderophloia*, and *E. tereticornis* (LAMR 2001). Understoreys ranged from grassland through to shrubby dominated by *Banksia spp.*, *Hakea florulenta*, *Hibbertia stricta*, *Hovea acutifolia*, *Melaleuca sieberi* and *Pultanea villosa*. Understoreys, including herbaceous species such as *Cyperus exaltus*, *Fimbristylis spp.*, *Goodenia rotundifolia*, *Juncus usitatus* and *Viola hederacea* were common, as were those consisting of *Gahnia aspera*, *Dianella caerulea* and *Lomandra longifolia* (LAMR 2001).

2.4 General Methods

2.4.1 Site selection

The basis for site selection, developed from Chatto (1996) and McCarthy *et al.* (1999) dictated from where and when within the study area the samples were obtained. The primary aim was to obtain an adequate number of samples from each vegetation type as accumulation characteristics may differ between each vegetation assemblage as has been demonstrated in other studies (Chatto 1996, Bresnehan 1998). Sampling sites were selected based on five criteria. These criteria were in order of importance and each potential sampling site was assessed for suitability. The criteria were;

1) <u>Levels of disturbance;</u>

Sites which displayed evidence of a high degree of disturbance (i.e. clearing, high proportion of weeds) were avoided where possible. This evidence was in the form of large amounts of garbage, recent tree removal or clearing of vegetation and wheel tracks from 4WD vehicles and motorbikes. These sites had either observable lower fuel loads due to tree removal and vegetation clearing or alternatively, higher fuel loads due to increased leaf and twig material due to disturbances created by recreational and unlawful activities such as dumping of garden waste. Although, sites experiencing this level of disturbance have an artificial source of litter accession in addition to natural processes they may be more characteristic of remnant

bushland at the urban interface and therefore representative of the fragmented urban areas of southeast Queensland.

2) Known fire age;

Sites of known fire age were sampled in preference to sites of unknown fire age, to provide a means of producing a continuous accumulation growth curve for each vegetation type over time.

3) Canopy class;

Sites that did not clearly meet either of the above vegetation types or were intermediate between them were not sampled.

4) Topography & Soils

To reduce the effect of these variables, sites were chosen that displayed similar soil types and topographical features where possible.

5) Accessibility;

Site accessibility was considered in the selection process, both for ease of collection and for potentially subsequent re-sampling.

2.4.2 Site descriptions

Once selected each site was described in terms of its basic physical, spatial and vegetation characteristics. A list of observable vascular plants was recorded, along with details of foliage projective cover (FPC) and any other notable features that distinguished sites from others (i.e. changes in slope or aspect).

The FPC was calculated using the method outlined in Stock (2005) and Zancola *et al.* (2000) whereby digital photographs were taken of the canopy and converted into black and white

pixels by using the Imagepro (v3) computer program (Hacker 2001). The ratio of black to white pixels indicated the percentage foliar cover at each sampling point.

Rainfall data for each site was obtained from the Bureau of Meteorology (BOM) records for Redland Bay. At each site the average rainfall was taken for the year following the most recent fire event.

2.4.3 Dating methods

The time since last fire for each site was obtained from documented council and Queensland Fire and Rescue Service records. For those sites where fire history was either unknown or questionable (5 sites in total) simple field dating techniques were adopted by counting tree growth rings on fire-scarred *Leptospermum sp.* or *Eucalypt sp.* as outlined in Bresnehan (1998).

2.4.4 Fuel sampling

Field and laboratory techniques used were similar to those used by and Chatto (1996) and Bresnehan (1998). Five columnar quadrats of 0.5 m^2 at each sampling site were taken. The column extended 0.5 m above the ground to include near surface fine fuels i.e. small shrubs, grasses and sedges (Figure 2.1).

Figure 2.2 Photograph of 0.5 m quadrat used to take fuel samples. (Photo: J. Gilroy)

The protocol for distributing the quadrats within the site involved firstly determining the size of the site. The first sampling point was selected by moving 20 meters into the site away from the edge of a track, road or boundary to reduce edge effects. The sampling quadrat was then randomly thrown towards the centre of the site. From this point, the subsequent sampling points were taken along a line transect at 50 m intervals.

The fuel collected was limited to the finer materials (of up to 6 mm diameter for dead vegetation and 2 mm for live vegetation), or 'flash fuels', which have been shown in studies to be the key component of the total biomass capable of supporting a fire front (Walker 1981, Tolhurst & Cheney 1999). For each quadrat sampled, the fuel load was divided into four categories.

a) Leaves (including grass),
b) Twigs,
c) Bark,
d) Residual (includes flowers, fruiting bodies and semi-decomposed leaf, twig and bark material and any other unidentifiable material).

The perimeter of the inside of the quadrat was cut using secateurs, including that of grasses and plants growing within the quadrat. All surface fine fuel within the quadrat was then transferred into labeled paper bags for later oven drying, weighing and sorting.

2.5 Laboratory Method

The samples transferred into paper bags for oven drying at 70^0C until there was no weight change (between 72-96 hours), which indicated complete moisture removal. To avoid contamination and spillage Detpak© brown paper bags were used to dry samples as the paper allows passage of water vapour through the walls of a sealed bags.

2.5.1 Drying and weighing

After drying, the samples were weighed once removed from the oven. Samples were weighed immediately, as they are able to take up atmospheric moisture at a rate of 0.02 g s^{-1} (Bresnehan 1998). Each sample bag is weighed first and then immediately emptied and the

empty bag weighed. The net dry sample weight is obtained by taking the difference between the initial wet weight and the final dry weight.

2.5.2 Site data sheets

Fuel dry weight data were collated on Excel™ spreadsheets, one per vegetation type. For each site the following variables were measured;

Table 2.1 All measured variables and their units, for each sampling point, at each site.

Variable	Units
Actual Surface Fine Fuel load	Tonnes per hectare (t/ha)
Maximum Estimated Surface Fine Fuel load	Tonnes per hectare (t/ha)
Minimum Estimated Surface Fine Fuel load	Tonnes per hectare (t/ha)
Leaves	Tonnes per hectare (t/ha)
Twigs < 6 mm	Tonnes per hectare (t/ha)
Bark	Tonnes per hectare (t/ha)
Fuel Depth	Millimeters (mm)
Foliage Projective Cover	Percentage (%)
Rainfall 1 year post-fire event	Millimeters (mm)

Chapter 3. Fuel Accumulation and Models

3.1 Introduction

Fuel accumulation models are used to estimate and predict fuel quantities worldwide (Anderson 1987, Conroy 1993). They are now considered to be an essential part of the decision making process and are widely used by land management agencies (McCarthy *et al.* 1999). Fuel accumulation is a result of many separate and related influencing factors and as such, are complex systems that are difficult to completely explain (Gill 1997). The total fuel load will depend on the rates of accession and decomposition of litter (Conroy 1993, Chatto 1996). This is further reliant on the vegetation type, productivity of the overstorey and understorey, the density of the vegetation and environmental conditions of the area (Millar & Urban 2000).

The rates of fuel accumulation in Australian dry sclerophyllous vegetation are known to be low by world comparison (Pressland 1982, Chatto 1996). Studies (Raison *et al.* 1983, Simmons & Adams 1986, Fogarty 1993) have indicated that in eucalypt-dominated forests, the bulk density of fuel accumulates for the first 4-5 years post-fire after which, it remains steady as invertebrate fauna return and equilibrium between litterfall and decomposition is achieved (York 1999, Brookes *et al.* 2004). A select example of the accumulation within dry-eucalypt ecosystems is provided in Table 3.1.

Table 3.1 Summary of fuel loads obtained from other studies in eucalypt communities Australia (sources provided).

Location	Vegetation Type	Years Post-fire	Fuel Quantity t/ha	Source
Australian Capital Territory	*E. rossi / E. macrorhyncha*	5.6 30	13.5 15.0	Davis 1976
Kosciusko, NSW	*E. pauciflora*	3.0 36	6.6 12.2	Gill *et al.* 1976
Wombat Forest, VIC	*E. obliqua / E. radiata / E. Rubida*	3-10 > 20	15.8 18.2	Tolhurst & Kelly 2003

Sydney, NSW	Eucalyptus woodlands	0.1	6.7	Conroy 1993
		1.3	6.9	
		3-6	15.2	
		6-10	18.3	
		10-20	22.4	
		> 20	22.4	

In dry sclerophyll forests, it was found that areas with a canopy cover of 50% or above, the build up in fuel load is relatively swift for the first 10 years, reaching an equilibrium fuel load of about 15 t/ha (Brookes *et al.* 2004). Conversely, in areas with a well-developed understorey, fuel loads can continue to increase for over 25 years (Tolhurst & Cheney 1999). Comparatively, in wet sclerophyll forests, fuel can build up for over 30 years before reaching any level of equilibrium (Guinto *et al.* 1999).

Fuel accumulation models based on this type of scientific research are an essential land manager's tool helping to realistically estimate and predict potential fire behaviour. More importantly, fuel accumulation models can assist in determining when land management practices such as hazard reduction are applied. The most commonly used model for fuel accumulation is Olson's (1963) negative exponential model to quantify litter accumulation and it has since been used as a descriptor of fuel accumulation (Sandercoe 1990).

The model was developed based on data obtained from Northern America, providing a method of predicting litterfall in the natural environment by describing an asymptotic relationship between litterfall and decomposition rate using the following equation:

$$X_t = X_{ss}(1-e^{-kt})$$

Where: X_t = weight of fine fuel per unit area *t* years after fire
X_{ss} = weight of fine fuel accumulated under steady state conditions
k = decomposition constant (yr^{-1})
t = time since fire (yr)

It must be noted that, although fuel accumulation in eucalypt forests can be described using this equation, it is an oversimplification of the factors that can affect fuel accumulation and as

such has been modified to reflect local conditions on a number of occasions as outlined below in Table 3.2. (Conroy 1993, Fernandes & Botelho 2003).

Table 3.2 Summary of fuel accumulation models derived from studies in Australian Eucalypt forests.

Dominant Vegetation	Site Location	Rainfall (mm)	Model	Source
E. pilularis	Seal Rocks, NSW	1400	$X_t = 1.67\,(1\text{-}e^{-0.31t})$	Fox *et al.* 1979
Eucalypt woodlands	Sydney, NSW	-	$X_t = 23.57(1\text{-}e^{(-0.2774t)})$	Conroy, 1993
E. obliqua, *E. radiata,* *E. rubida*	Wombat State Forest, Victoria	-	$X_t = 8.28\,(1.47\text{-}e^{-0.506t})$	Tolhurst & Kelly, 2003
E. obliqua, *E. radiata,* *E. sideroxylon,* *E. polyanthemos,* *E. gonidocalyx*	Victoria, Australia	700	$X_t = 16.9\,(1\text{-}e^{-0.44t})$	Simmons & Adams, 1983
E. pauciflora *E. dives* *E. delegatensis*	Unspecified sub-alpine region in Australia	-	$X_t = 11.1(1\text{-}e^{0.11t})$ $X_t = 29.4\,(1\text{-}e^{0.31t})$	Raison *et al.* 1983
Eucalyptus crebra *Eucalyptus moluccana* *Eucalyptus macrorhyncra*	Chiltern, VIC	685	$X_t = 7.15\,(1\text{-}e^{-0.876t})$	Chatto, 1996
Eucalyptus signata	Cooloola, QLD	-	$X_t = 7.3\,(1\text{-}e^{-0.64t})$	Sandercoe 1990

It is interesting to note that the decomposition constants are fairly consistent across eastern Australia even though there are large variations in climatic conditions, vegetation and rates of accumulation.

A continuous litter fall model adopted by Fox *et al.* (1979) has been suggested to better suit Australian conditions. Fox *et al.* (1979) states that, in eucalypt forests, an accumulation model using two parameters; (1) steady-state accumulation and (2) the rate of accumulation, should be sufficient to describe litter accumulation. Following these studies, Fogarty (1993), Conroy (1993) have found that the assumptions of Olson's (1963) model of constant litter fall and decomposition rates over time are often not met in eucalypt forests in Australia because these forests have complex age structures that vary due to season, temperature and rainfall. The assumed constant value of k can be argued to be erroneous in itself, as it is known that

decomposition rates fluctuate over time (Walker 1981, Raison *et al.* 1983). However, if the other factors are known, the decomposition constant can then be enumerated.

Two predictive models were developed by McCarthy & Tolhurst (2001) based on the Fire Danger Index (FDI) and overall fuel hazard. Both models predict that as fire danger increases the benefits of a previous fuel reduction burn starts to reduce (Tolhurst *et al.* 1992). McCarthy & Tolhurst (2001) predicted that a fuel reduction burn will only play a role in helping to reduce the severity of the fire and in assisting fire fighters with suppression for the first 4 years post-burn. This research has led to fire management strategies involving the manipulation of fuel and frequency of fire. Even so, as previously mentioned, these models are based on site specific conditions, which are as yet undetermined for southeast Queensland.

The purpose of this study is to investigate fuel accumulation in two different vegetation types (outlined in sections 2.3.1 & 2.3.2) and to develop a predictive model with which to estimate surface fine fuel loads for these vegetation types.

3.2 Methods

All samples were collected across the study area using methods outlined in section 2.4.

3.2.1 Data analysis

Exploratory data analysis was used to examine the raw data before any analyses were performed to ensure that assumptions were not violated.

Non-linear regression analysis

Non-linear accumulation curves were fitted for the two vegetation types and time since fire using the statistical computer program Statistica™ (2002). Non-linear curve estimates are, theoretically, a better fit to the data, similar to the equation modified from that presented in Conroy (1993):

$$y = y_{\max}(1 - e^{-kx}).$$

The $y_{\max}$ component of the equation is the point at which the values for y have reached a steady state. The k component indicates the rate of litter decomposition for the category. At $y_{\max}$ the litter accession (A) is equal to litter decomposition (k), thus $y_{\max}$ equals A/k (Olsen,

1963). The variable *x* is the elapsed time since the site was last burnt. This makes theoretical sense and is in line with other studies, in that following fire, fuel accumulates rapidly and the system reaches equilibrium (rate of accumulation to decomposition) (Fogerty 1993, Chatto 1996, Brandis & Jacobson 2003).

To estimate the parameters for the non-linear regression modeling, the Least Squares method was used, whereby the estimates of the parameters are obtained by minimizing the sums of squared differences between the observed and the fitted values (Quinn & Keough 2002).

Further non-linear analysis involving all the variables was beyond the scope of this study and was not attempted.

Multiple regression analysis

Preliminary data analysis indicated any potential linear relationships between fuel quantity and the other variables (Appendix 4). Multiple regression analysis was used to examine the relationship between fuel quantity and time since fire, foliage projective cover, rainfall (1 year post-fire) and fuel depth.

3.3 Results

3.3.1 Surface Fine Fuel Characteristics

A total of 145 surface fine fuel samples were taken over the period of the study, 5 from each transect on each occasion. Table 3.3 provides a summary for each site measured, including the vegetation type, the mean fuel depth, the average surface fine fuel quantity (with standard error) the average foliage projective cover (FPC) and the average annual rainfall (1 year post-fire event) at each site. The data is ordered by the time past since the last fire event. The extent of fire history in this study ranged from 0.8-22 years.

For *Eucalyptus major/Corymbia citriodora* open forest total surface fine fuel loads ranged between 6.32-16.09 t/ha with an overall mean (± S.E.) of 12.44±1.34 t/ha. The individual samples ranged from 4.83-21.93 t/ha with the largest being almost ten times greater than the mean. The variation found within the surface fine fuel load clearly indicates the patchy

distribution associated with fuel loads across the study area. It also indicates the unevenness of fuel that can accumulate in areas after a fire event.

In this study, low fuels were associated with open canopy areas or near fallen logs whereas higher fuel loads were associated in areas with dense canopy cover and noticeable fuel build up near the base of senescing trees or shrubs. The fuel depth ranged from 8.6-24.95 mm, (mean 18.66±1.78 mm). The deepest fuel bed depth measurement that was taken over the study period was 35 mm.

For *Eucalyptus racemosa* open woodland, the total surface fine fuel loads ranged between 3.77-19.51 t/ha with an overall mean of 11.84±1.58 t/ha. The individual surface fine fuel quantities for this vegetation type ranged between 0.97-33.26 t/ha thereby indicating the great disparate heterogeneity of fuel found within the study area. The fuel depth ranged from 7.4-34 mm averaging 17.03±2.76 mm. The deepest fuel bed depth measurement taken for this vegetation type was 57 mm.

Table 3.3 Summary of all 145 fuel measurements taken at each site in Redland Shire, March-September 2005.

Site	*Location*	*Vegetation Type*	*Time Since Fire (years)*	*Mean Surface Fine Fuel Load (t/ha)*	*Standard Error of the mean*	*Mean Litter Depth (mm)*	*Mean Foliage Projective Cover %*	*Mean Rainfall (mm) 1 year post-fire*	*Estimated Surface Fine Fuel Hazard*
1	Greater Glider Conservation Area	W	0.8	3.77	0.88	7.4	36.81	98.13	L
2	Cleveland Sewage Treatment Works	W	1.2	4.48	0.59	10.2	30.60	151.33	L
3	Judy Holt Sportfield	W	2	7.5	1.87	8.8	34.82	60.16	L
4	Harrogate Terrace Reserve	W	4.5	15.32	1	19.4	55.06	86.42	M
5	Scribbly Gums Conservation Area (Block 11)	W	6	8.94	1.76	17.2	Not taken	138.3	M
6	Cleveland Sewage Treatment Works	W	6	6.56	0.22	34	51.7	138.3	H
7	Mc Millan Rd Reserve	W	7	11.64	1.55	19.68	14.34	97.86	M
8	Scribbly Gums Conservation Area (Block 10) & Birkdale Bushland Refuge	W	8	12.89	0.84	12.70	33.10	74.46	L
9	Scribbly Gums Conservation Area (Block 11)	W	9	11.90	1.44	12	52.1	102.31	L
10	Scribbly Gums Conservation Area (Block 13)	W	10	14.35	2.51	Not taken	40.56	76.58	-
11	Wellington St Reserve	W	14	12.54	1.26	17.2	45.88	105.36	M
12	Enterprise St/Swallow St Reserve	W	18.5	15.35	2.04	23.8	60.68	119.74	M

13	Wellington St Reserve	W	20	15.68	1.92	17	60.2	98.16	M
14	Enterprise St/Swallow St Reserve	W	21	19.51	3.69	18	44.64	110.06	M
15	Greater Glider Conservation Area	W	22	17.19	2.15	21	62.76	151.33	M
1	Mc Millan Rd Reserve	F	3	6.32	0.48	8.6	31	68.78	L
2	Ford Rd Conservation Area	F	8.5	13.78	1.88	22.40	52.58	121.71	M
3	Eastern Escarpment Conservation Area	F	11	15.70	0.64	24.95	56.35	79.5	M
4	Summit St Reserve	F	11.5	8.94	1.08	15.60	55.35	104.99	M
5	Summit St Reserve	F	14.5	13.82	2.10	20	32.71	63	M
6	Ford Rd Conservation Area	F	15	16.09	1.85	20.4	57.16	128.33	M

(W = *Eucalyptus racemosa* open woodland, F = *E. major/ Corymbia citriodora* open forest). (L = Low, M = Medium, H = High, VH = Very High fuel hazard ratings estimated from the Overall Fuel Hazard Guide (McCarthy *et al.* 1999).

3.3.2 Non-linear curve estimation

Table 3.4 Non-linear curve estimation models for both vegetation types.

***E. major/C. citriodora* open forest**
Model: Fuel Load (t/ha) = s*(1-1/(r**(Time Since Fire + a)))*(s>0)*(r>1)
y=(61.976)*(1-1/((1.00496)**(x+(41.5212))))*((61.976)>0)*((1.00496)>1)
***E. racemosa* open woodland**
Model: Fuel Load (t/ha) = s*(1-1/(r**(Time Since Fire +a)))*(s>0)*(r>1)
y=(18.0685)*(1-1/((1.12814)**(x+(1.32973))))*((18.0685)>0)*((1.12814)>1)

In line with previous studies, (Birk 1979, Fogarty 1993, Chatto 1996, Bresnehan 1998, Brandis & Jacobson 2003) non-linear negative exponential models best explained the accumulation of fuel in different vegetation ecosystems. With this in mind, non-linear curve estimation were used in this study in order to provide reliable predictions of the distribution of the data.

The non-linear models predicting surface fine fuel load in the *E. major*/*C. citriodora* open forest and *E. racemosa* open woodland are plotted untransformed in Figures 3.1 and 3.2 respectively. For the *E. major/C. citriodora* open forest, non-linear estimation was not able to provide a reliable fuel-growth curve. This was due to the absence of available sites with recent (below 5 years) or extended (past 16 years) time since fire events. Based on this information it was decided that further non-linear or linear analysis would not provide meaningful results and was thus abandoned for *E. major*/*C. citriodora* open forest.

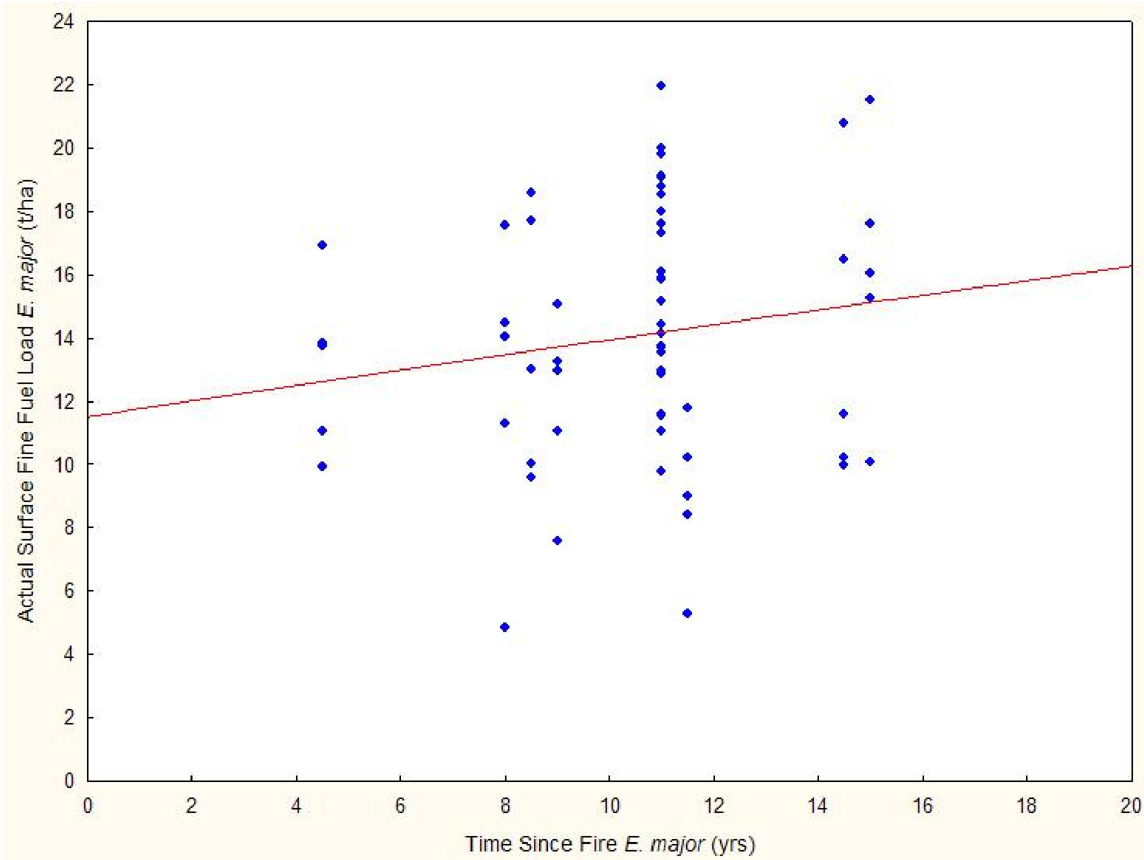

Figure 3.1 Curve Estimation for *E. major / C. citriodora* open forest. Blue dots represent the raw data, the red line represents the estimated curve fitted for the data.

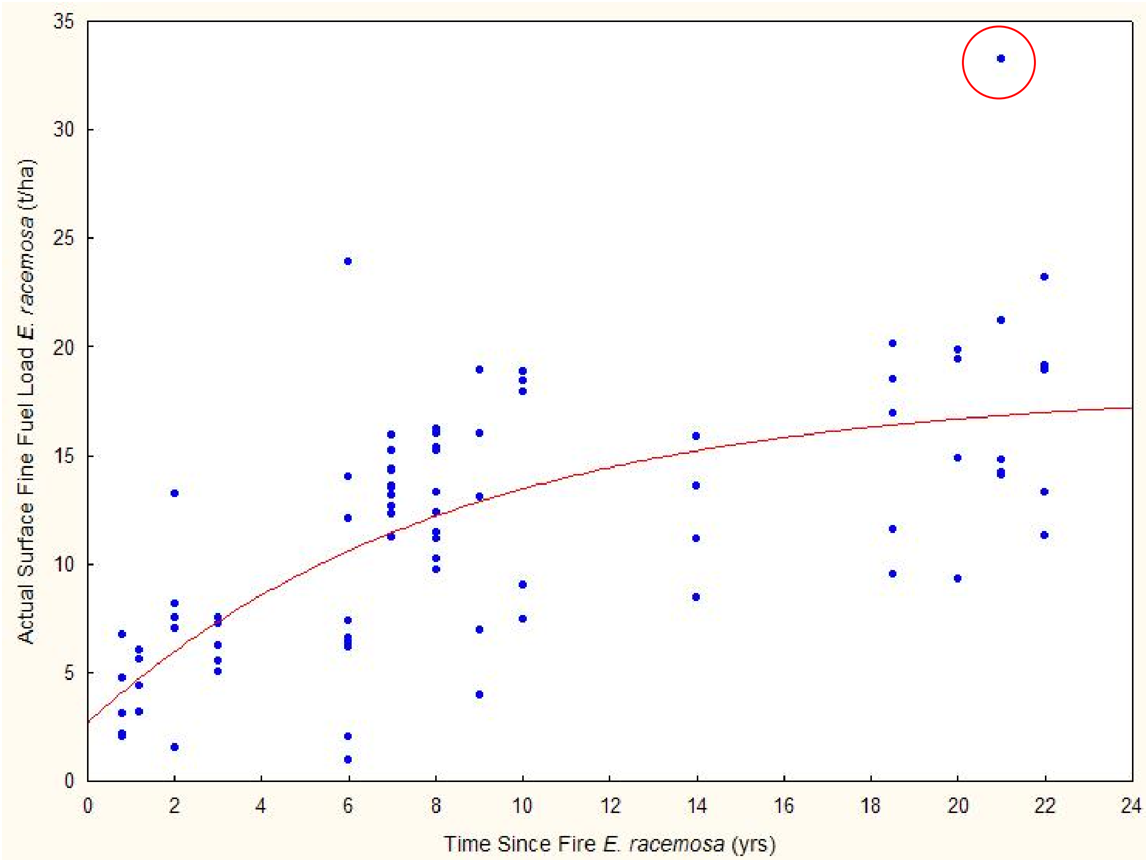

Figure 3.2 Curve fitted for the raw data of *E. racemosa* open woodland. Blue dots represent the raw data. The red line represents the estimated curve fitted for the data. The red circle is identifying an extreme outlier.

Figure 3.2 shows the negative exponential relationship between surface fine fuel quantity and time since fire for the *E. racemosa* open woodlands. The relationship between time since fire and fuel quantity displays what can be identified as three separate stages in fuel accumulation. Initially, there is a rapid accumulation of surface fine fuel in the first 6 years followed by a more steady increase in fuel quantity up to 10 years post-fire. Finally, fuel accumulation appears to plateau as it approaches equilibrium after approximately 16 years. The fitted curve suggests that in long unburnt fuels the quantity of surface fine fuel load approaches 15 t/ha with the majority of this quantity being reached between 10-18 years post-fire.

Close inspection of the raw data reveals an outlier (circled in figure 3.2) that may be influencing the curve-fit. It is located at 21 years post-fire and has a high surface fine fuel load of 34 t/ha. It was noted during sampling that this point was located in an area of high

density of *Allocasuarina littoralis* (out of character with the other sites measured for this vegetation type) and thus a higher than normal amount of needles comprised the surface fuel bed. To determine if this point was influencing the dataset significantly it was removed from the analysis. With the curve refitted, minimal differences were made to the model and data point was therefore left in the dataset.

The fitted curve does not pass through the origin indicating that immediately after a fire there will still be residual fuel left unburnt. Data was not able to be obtained closer to the fire event as recently burnt areas were unavailable within this timeframe. From the fitted curve however, it is estimated that approximately 3 t/ha is expected at the time of a fire event thereby indicating that in previous fires at these sites all potential surface fine fuel was not consumed and thus remained available. This finding is consistent with others in Australian eucalypt forests and woodlands (Tolhurst 1992, Burrows 2001, Fernandes & Botelho 2003). Even in high intensity fire events some fuel remains on the ground, with changes in wind direction and topography contributing to altered fire behaviour.

This relationship obtained from the fitted curve does not take into account the variability in surface fine fuel associated with FPC and rainfall or fuel depth as non-linear curve estimation using greater than one parameter is highly complex and beyond the scope of this study. Further, it is also important in order to provide a careful fuel model predictor or system, this input component needs to be kept relatively simple and applicable. With this in mind, multiple linear regression techniques investigating the relationship of fuel quantity and time since fire, fuel depth, FPC and rainfall were further analysed in the following section. Linear regression has been used in other studies to explain the fuel growth potentials for $\underline{x} + \underline{y}$ (Raison *et al.* 1983, Fogarty 1993).

3.3.3 Multiple linear regression techniques

Tables 3.5 and 3.6 summarises the output from the multiple linear regression model (from SPSS ® v12). The model suggests that time since fire, fuel depth and FPC are reliable predictors of surface fine fuel quantity and they can independently explain a total

of 68% of the variation within the data set (Table 3.5-3.6). The variation also suggests that fuel is related to other factors other than those measured here.

The regression models were subjected to a model fit test based on data residuals. Graphing the residual (*observed minus predicted*) with fire age for each site indicated if the model was consistently over-predicting or under-predicting fuel weight in the accumulation curve (Figure 3.3).

Table 3.5 Linear regression models for *E. racemosa* open woodland.

***E. racemosa* open woodland**	**Sig.**	**Adjusted R^2**
Model 1: Fuel Load (t/ha) = *x (Time since fire) + y (FPC) + z (Fuel depth)* +x_1 *(Rainfall Average 1 year post-fire)*	0.000	.692
Model 2: Fuel Load (t/ha) = *x (Time since fire) + y (FPC) + z (Fuel depth)*	0.000	.679
Model 3: Fuel Load (t/ha) = *x (Time since fire) + y (FPC) + z (Fuel depth)* +x_1 *(Rainfall Average 1 year post-fire)*	0.000	.708
Model 4: Fuel Load (t/ha) = *x (Time since fire) + y (FPC) + z (Fuel depth)*	0.000	.706

Table 3.6 Linear Regression data output from SPSS for *E. racemosa* open woodland. NB: Bold coefficients indicate statistically significant contribution to regression model.

		Unstandardized Coefficients		Standardized Coefficients		
Model		B	Std. Error	Beta	t	Sig.
1	(Constant)	3.364	2.122		1.585	.118
	Fuel_Depth	**.341**	**.071**	**.423**	**4.795**	**.000**
	Time_Since_Fire	**.328**	**.066**	**.415**	**4.994**	**.000**
	FPC	**.084**	**.028**	**.243**	**3.036**	**.004**
	Rainfall	-.035	.018	-.150	-1.937	.057

		Unstandardized Coefficients		Standardized Coefficients		
Model		B	Std. Error	Beta	t	Sig.
2	(Constant)	-.059	1.200		-.049	.961
	Fuel_Depth	**.286**	**.067**	**.355**	**4.293**	**.000**
	Time_Since_Fire	**.321**	**.067**	**.406**	**4.789**	**.000**

	FPC	**.100**	**.027**	**.291**	**3.728**	**.000**

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
3	(Constant)	.764	2.083		.367	.715
	Fuel_Depth	**.282**	**.073**	**.350**	**3.844**	**.000**
	FPC	**.098**	**.026**	**.284**	**3.733**	**.000**
	Ln_Time_Since_Fire	**2.532**	**.466**	**.448**	**5.437**	**.000**
	Rainfall	-.021	.018	-.090	-1.185	.241

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
4	(Constant)	-1.293	1.155		-1.119	.267
	Fuel_Depth	**.243**	**.066**	**.302**	**3.690**	**.000**
	FPC	**.106**	**.025**	**.309**	**4.217**	**.000**
	Ln_Time_Since_Fire	**2.583**	**.465**	**.457**	**5.554**	**.000**

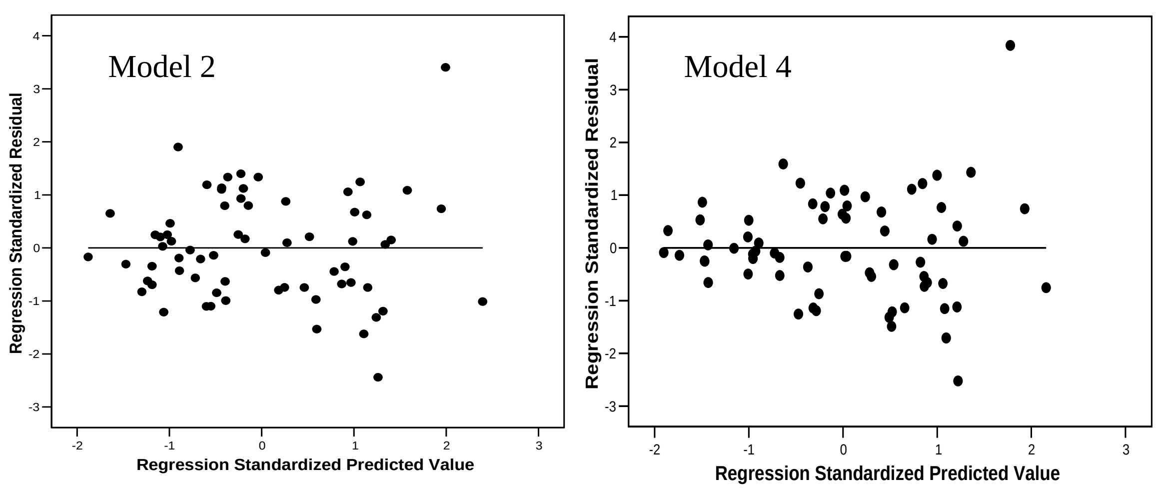

Figure 3.3 Scatter plots of the standardised residuals for a) Model 2 and b) Model 4showing the distribution of the data points around the mean for *E. racemosa* open woodland.

From the analysis it was found that time since fire accounted for most of the variability in surface fine fuel quantity data. This was closely followed by fuel depth and FPC

(Table 3.5-3.7). Time since fire and fuel depth explained almost one third of the variation in surface fine fuel samples for *E. racemosa* open woodland.

Further exploration of the data found that if the logarithm of 'time since fire' was calculated, the model was improved slightly. However, after visual inspection of the residual scatter plots for both the transformed and untransformed time since fire, it was decided that the analysis was to be conducted on the untransformed data sets as the residuals were more uniformly distributed than the transformed datasets (Figure 3.3).

Table 3.7 Parameters which explain the most variation of surface fine fuel.

Parameter	% Variation
Time since fire	32 ($p < 0.000$)
Fuel depth	29 ($p < 0.000$)
Foliage projective cover	10 ($p < 0.000$)

3.4 Discussion

3.4.1 Non-linear Curve Estimation

The negative exponential model provides a good fit to the data obtained for *E. racemosa* open woodlands in Redland Shire. It is acknowledged that although fuel accumulation involves many more processes than simply litter accumulation and decomposition, the current model accurately and precisely describes this relationship and is consistent with other studies that support this type of fuel growth curve (Olson 1963, Luke & McArthur 1978, Fogarty 1993, Chatto 1996, Brandis & Jacobson 2003, Smith *et al.* 2004). It should be noted that there are a number of assumptions associated with the use of non-linear curve estimates, including; a steady state relationship between litterfall and litter quantity, a constant litterfall and decomposition rate, fuel that is uniform over the area studied and finally, that all fuel is consumed in a fire (Olson 1963). With the use of any model the assumptions do not always agree with the actual dynamics.

Firstly, it is assumed that in Australian eucalypt forests and woodlands a steady state of fuel accumulation is achieved (Chatto 1996). Sandercoe (1990) predicts that from south (Victoria) to north (Queensland) steady state fuel loads decrease, decomposition increases and the time taken to reach equilibrium also decreases (Sandercoe 1990). It is assumed that this is primarily due to the increase in productivity and greater rates of decomposition through microbial activity (Sandercoe 1990). However, quantities of surface fine fuel found in this study are comparable with those of other Australian studies namely those of Simmons & Adams (1986) in dry sclerophyll urban fringe forests of Victoria and Raison *et al.* (1983) for dry sclerophyll forests in the Blue Mountains of NSW, *E. sieberi* forests of coastal NSW and also Conroy (1993) in the eucalypt woodlands of the Sydney region. This indicates that the trend identified by Sandercoe (1990) may not be appropriate for all eucalypt forest types and fuels, particularly in this study.

Secondly, it is assumed that litterfall is consistent for Olson's (1963) model. A number of studies have indicated that litterfall varies seasonally with highest litterfall rates recorded in summer (Westman & Rogers 1977, Simmons & Adams 1986) and the lowest in winter for Australian eucalypt forests and woodlands (Tolhurst *et al*. 1992, Gill 1997). Taken over a (sufficient) period of time, as in this study, the effects of seasonality may be further minimised. Further, fluctuations in litterfall, and thus fuel quantity, may be dependent more so on fire history, disease, local characteristics, vegetation density and flora species present and also due to episodic climatic events such as long periods of drought and higher than average rainfall (Chatto 1996, Gill 1997). For the present study site specific effects such as individual tree death or senescence at particular sampling points are more likely to influence the variability within the dataset. This is evident with the increase in variation of the standard error of the mean over time. Fox *et al.* (1979) and Brandis & Jacobson (2003) have recognised that although fluctuations can be great, Australian eucalypt forests best follow a continuous litterfall model rather than a discrete model.

Thirdly, the negative exponential fuel accumulation curve assumes that surface fine fuel is distributed uniformly, both vertically and horizontally across the study site (Olson 1963). As can be expected, the natural processes occurring at a particular location will influence the structure and patchy distribution of fuels thus causing this assumption to be extraneous and particularly difficult to measure factor into the model (Catchpole 2002). The quantity and continuity of the remaining residual fuel from previous fires also depends on previous fire history (intensity and frequency) (Tolhurst *et al.* 1992).

Finally, the model also assumes that previous fires at the site have removed all available fuel, and as such, do not contribute to the fuel load post-fire (Olson 1963). This may be true for very high intensity fires that could consume all available fuel, however, for low intensity fires or 'cool' burns this does not always happen (Bradstock *et al.* 1998). Low intensity fires may not burn fuels that have high moisture content or may not extend through the entire surface fuel profile and in the case of the present study some fuels were shown to extend some 43 mm deep. Therefore, fires would have to be quite intense to consume the entire surface fine fuel load, compared with studies such as those conducted by Tolhurst & Cheney (1999). Further, the data do not show zero t/ha at the time of the fire (i.e. $t = 0$) because it has been generally accepted that residual fuel remains after a fire (Tolhurst *et al.* 1992, Buckley 1992*b*, Burrows 2001, Tolhurst & Kelly 2003). The estimate of 3 tonnes per hectare of residual fuel in the present study is therefore realistic and in-line with studies conducted in other similar eucalypt communities elsewhere in Australia (Tolhurst & Kelly 2003). In comparison to limited studies here in southeast Queensland, surface fuels have been found at either zero or close to zero post-fire event regardless of fire intensity (Sandercoe 1989). This has important implications for fire management as fuel may accumulate much more rapidly as indicated in the present study than expected due to fuel remaining post-fire.

As can be expected, the above mentioned assumptions have been violated on most occasions in Australian eucalypt vegetation studies (Chatto 1996). Studies have attempted to apply 'correcting factors' to the original negative exponential model including that of Conroy (1993) where time since fire and vegetation structure are taken

into consideration. However, Brandis & Jacobson (2003), show the use of Conroy's equation tended to overestimate actual fuel loads when applied to different locations. Other modified equations, based on the original, have also been found to be quite site specific and although they provide an excellent tool for estimating fuel loads, they do not provide enough information to be able to predict the behaviour of fire or to predict fuel accurately for any given year (Chatto 1996). Therefore, due to the widespread use of Olson's (1963) model, limited as it is, is still considered the most applicable when determining fuel accumulation across Australia (Fox *et al*. 1979, Brandis & Jacobson 2003).

3.4.2 Multiple Regression Analysis

Even though the non-linear curve estimation provided a reasonable predictor for fuel load in *E. racemosa* open woodland, the assumption that the model is based on can retard the usefulness of the model. Even though the negative exponential curve is better suited to actual conditions, multiple regression was also used. Linear regression is bounded by strict statistical boundaries which may provide for greater exploration of the data. Whilst it is acknowledged that fuel growth does not continue linearly with time, this may be explained in further studies which may examine longer time since fire than was examined in the present study. Until this is completed, the multiple regression model prepared in this study represents the best understanding of fuel growth for *E. racemosa* open woodland and comparable eucalyptus dominated woodlands in southeast Queensland.

The relationship between surface fine fuel quantity and time since fire, fuel depth, foliage projective cover (FPC) and rainfall (1 year post-fire) were investigated to determine if any or all of these parameters could provide a useful and accurate indirect estimation of surface fine fuel quantity. The multiple regression results indicate that fuel depth and foliage projective cover are good predictors of surface fine fuel quantity. Other studies have found that rainfall is strongly correlated with litterfall accumulation rates, as high rainfall is generally associated with higher productivity therefore contributing to the overall fuel quantity (Simmons & Adams 1983, Hutson 1985, Chatto, 1996). However

the rainfall analysis used in this study showed that rainfall (one year post-fire) did not contribute significantly to surface fine fuel quantity.

In line with previous research (Wilson 1993, McCarthy *et al.* 1999), this study has found a linear relationship between fuel depth and surface fine fuel quantity. It has been noted by several studies (Anderson 1982, McCarthy 1996, Sandberg *et al*. 2001) that fuel depth and structure can directly influence a fire's forward rate of spread and flame height. Chatto (1996) found that 44% of the variation in surface fine fuel quantities could be explained by fuel depth. Whereas in this study, 29% of the variation in their study of surface fine fuel quantity was explained by fuel depth. Fuel depth may also be affected by such things as compaction, sandy substrates and the overlying canopy and associated understorey (Tolhurst & Cheney 1999). In this study, it is assumed that these influences have remained relatively constant as specific vegetation types were chosen for sampling of which neither were on sandy substrates and the amount of FPC was measured and included in the analysis. Fuel depth has been used elsewhere in Australian eucalypt communities, (NSW and VIC) to estimate surface fine fuel quantity and this study has confirmed the potential for applicable use of this measurement in southeast Queensland (Fogarty 1993, Chatto 1996, McCarthy *et al.* 1999). In total, the multiple regression analysis explained 67% of the variability in the data. This is a good outcome given the considerable within and between site variation.

There is limited research into the use of foliage projective cover (FPC) as an estimate of surface fine fuel loading in Australia (Brandis & Jacobson 2003). A recent study conducted by Brandis & Jacobson (2003) employs the use of satellite images to determine site productivity, providing an estimate of the surface fine fuel levels. Even though this work provides 'useful' information on fuel loads within a given area, it did not to directly estimate surface fuel and how this is distributed beneath varying levels of canopy cover, which is known to directly affect fire behaviour.

Although, the linear regression draws a clear linear association of fuel load and FPC. FPC seems to provide a useful indicator of site productivity (more FPC = more growth =

potentially more fuel accumulation).This study has determined that FPC has the potential to be used in conjunction with fuel depth and known fire history to provide a reliable estimate of surface fine fuel loads in *E. racemosa* open woodlands. The ability to take a measure of fuel depth along with FPC and accurately estimate the surface fine fuel load will enable a more accurate estimation without the time-consuming task of collecting, drying and weighing a number of fuel samples. If successfully tested in other area it may be able to estimate the time since fire component at those sites where fire history is unknown or subjective. Further study to determine the applicability of this method is warranted and recommended.

3.5 Limitations

The linear growth of fuel, as predicted in this type of analysis, limits the applicability of the outcome. Regardless of the site productivity or vegetation species dynamics, there are no fuels that continue to accumulate at this rate. However, it should be noted that one crucial aspect of fuel load dynamics was not measured, that is, litter decomposition. This was because it was beyond the scope of this study as it is impossible to know the quantity of fuel loads at each site extending back some 22 years in time. If the litter decomposition information was calculated, this could be included into the model and adjustments for the rate of decomposition will allow for a more realistic fuel growth model. However, until the decomposition rate is known, the linear regression model presented here represents the best understanding of the fuel growth rates for *E. racemosa* open woodlands in coastal southeast Queensland.

Chapter 4. Comparison of Estimated & Actual Surface Fine Fuel Loads

4.1 Introduction

Fuel beds are structurally complex and vary widely in their physical characteristics and in their potential to affect fire behaviour and suppression efforts (Sandberg *et al.* 2001). This makes measurement of fuel intrinsically complicated. The following methods are currently available for sampling and estimating fuel loads in all vegetation types in Australia and internationally (Anderson 1981, McCarthy & Tolhurst 2001).

4.1.1 Satellite imagery

The use of satellite imagery is the newest technique where fuel loads can be estimated by classifying vegetation types depending on the satellite images. This information is then coupled with data on fire history and canopy turnover rate to estimate litterfall and consequently, fuel load (via this indirect method) (Brandis & Jacobson 2003, Reich *et al.* 2004). An advantage of this method is that it can be used for large areas that are often inaccessible (Brandis & Jacobson 2003). However, this method is quite costly, and currently is only a coarse estimate of fuel load, as it does not directly measure the key component to fire behaviour - surface fuels (Sanchez-Florez & Yool 2004). This is especially evident in densely forested areas where the imagery does not penetrate the canopy (Reich *et al.* 2004).

4.1.2 Direct assessment

The direct (gravimetric) method of assessment involves taking actual samples of fuel loads in the field (McCarthy *et al.* 1999). By using the weight of the oven-dried samples, the fuel load (in equivalent tonnes per hectare) can then be reliably calculated/estimated (Bresnehan 1998). The previous chapter used this method of assessment. This method is accurate and reliable but can be point specific and time consuming (Brandis & Jacobson 2003). Despite problems that can arise due to seasonality, Fox *et al.* (1979) found that the amount of litter on the floor of the forest showed very little variation throughout the year indicating that the *time of litterfall* (i.e. season or day) is less significant than that of the

quantity of litterfall and the individual components on fire behaviour. Other studies have acknowledged that, to date, direct assessment is the only reliable method of estimating forest fuels (Chatto 1996,Reich *et al.* 2004). As emphasised in the previous chapter, a number of assessments are needed in order to provide this level of site accuracy.

4.1.3 Visual assessment

The visual assessment method attempts to quantify variations in fuel along with an estimate of fuel load, continuity and the height of each fuel layer (Wilson 1993, McCarthy *et al.* 1999). In order to do this, fuel depth is estimated using a fuel depth gauge. The depth of the fuel is measured over a minimum of five points (within 2-3 m^2 of each sampling point) and the average used to estimate surface fine fuel load (McCarthy *et al.* 1999). An advantage of this method is that it captures a complete fuel view both vertically and horizontally (Catchpole 2002). Furthermore, this method is rapid, simple, inexpensive and properly executed, quite precise (McCarthey *et al.* 1999). The disadvantages in visually assessing fuel are that it requires calibration and may be open to wide misinterpretation by inexperienced users (Brandis & Jacobson 2003).

There are a number of visual aids and guides available for estimating fuel load (Wilson 1993, Bresnehan 1998, McCarthy *et al.* 1999). The aids incorporate photographic examples, tabulations and similarity charts that assist in selecting the appropriate fuel model for a site (Cheney 1981, Anderson 1982). The *Overall Fuel Hazard Guide* is an example of the visual assessment method and is currently the most widely used method to estimate potential fuel load for land managers in southeast Queensland (McCarthy *et al.* 1999). This guide is based on a number of criteria ranging from assessing the surface, near surface, elevated and bark fuels using classes ranging from Low to Extreme (The Overall Fuel Hazard Guide is reproduced in Appendix 1). The final determination of the fuel rating is completed using comparisons with photographs from the visual guide and descriptors with the site. The guide was originally developed in southern Victoria based on information from Victorian eucalypt forests indicating that it may not be the most reliable or relevant tool for other forest ecosystems including those of southeast Queensland (Wilson 1993, Tolhurst *et al.* 1992, McCarthy *et al.* 1999). It is therefore

important to determine the accuracy of this guide for southeast Queensland conditions, including dry eucalypt forests and woodlands in the region.

4.2 Methods

All data were collected at the same time as that in section 3.2 using the following methods.

4.2.1 Actual surface fine fuel loads

The sampling regime used the same surface fine fuels as collected in section 2.4.4.

4.2.2 Fuel-depth measurement

At each quadrat, a 50 cm metal ruler and a slotted cardboard disc (15 centimeters in diameter) were used to determine the height of the litter layer (Figure 4.1). A total of five measurements were taken by randomly throwing the ruler around the sampling point and sliding the ruler through the middle of the cardboard with gentle hand pressure. The five values were then grouped and averaged to obtain an average litter depth for that sampling point. The average depth at each quadrat was used to estimate the surface fuel load using the Overall Fuel Hazard Guide (McCarthy *et al.* 1999).

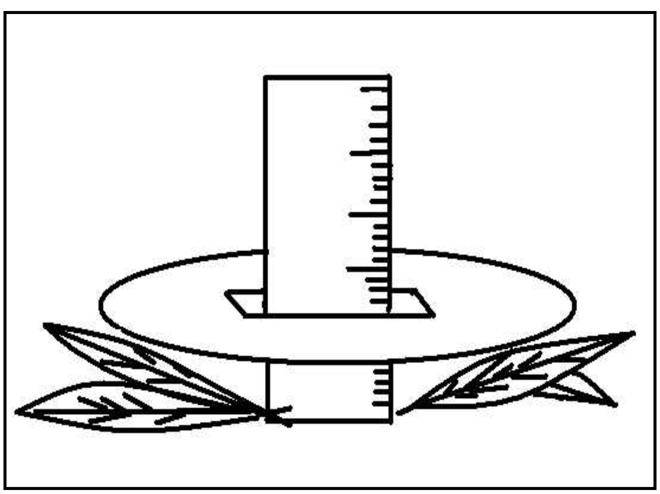

Figure 4.1 Schematic of fuel-depth gauge (reproduced from McCarthy *et al.* 1999)

4.2.3 Data analysis

The estimated surface fine fuel load obtained from the Overall Fuel Hazard Guide was plotted against the actual surface fine fuel load. This provided a visual indication as to the accuracy of the estimate given by the guide.

4.3 Results

4.3.1 Eucalyptus major / Corymbia citriodora open forest

The Overall Fuel Hazard Guide was used to estimate surface fine fuels at each sampling point along with collecting fuel samples for comparison. The data sets for the maximum estimated surface fine fuel for each vegetation type were plotted against the actual surface fine fuel load (in t/ha) for each vegetation type. Figures 4.2-4.3 represent the data obtained for the minimum and maximum visual estimates against that of the actual surface fine fuel loads for each sampling point.

Figures 4.2-4.3 clearly show that, for this vegetation type, the surface fine fuel estimation from the Overall Fuel Hazard Guide is well below the actual surface fine fuel load. This has some important implications in relation to the continuous independence of the Overall Fuel Hazard Guide in southeast Queensland.

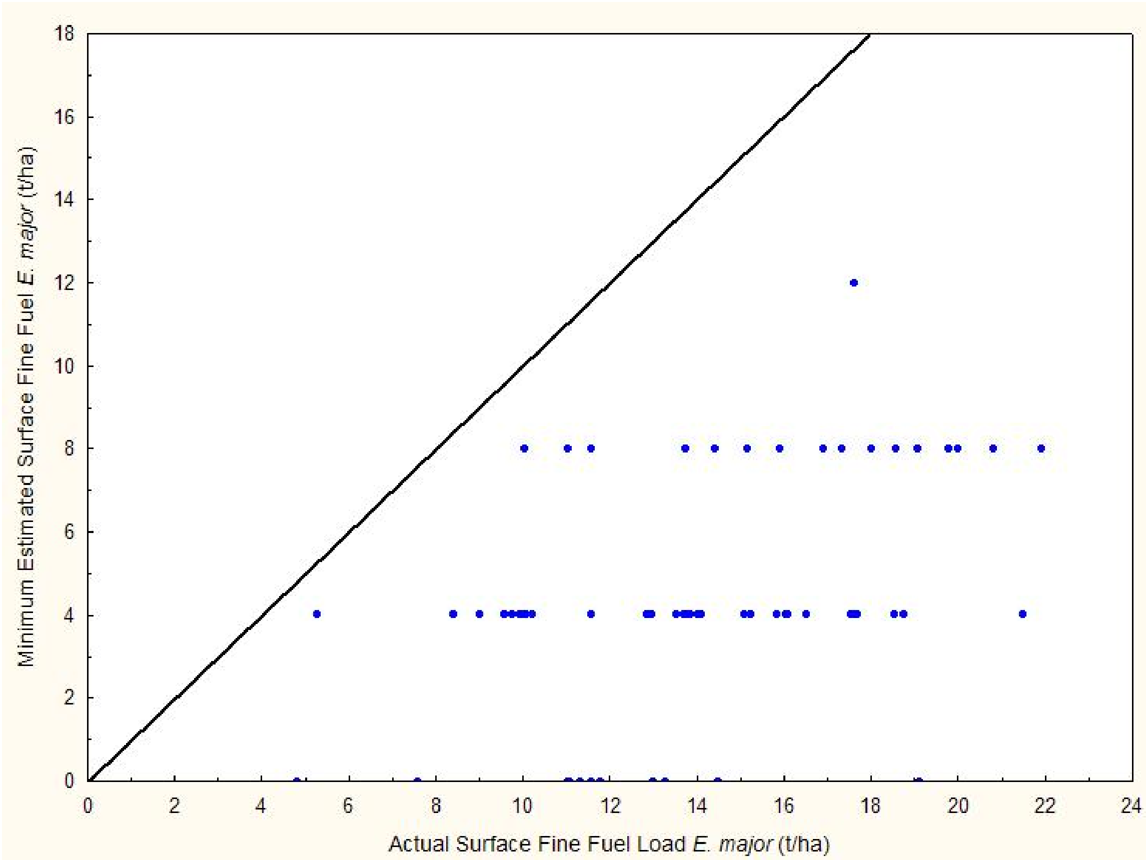

Figure 4.2 Comparison between the Overall Fuel Hazard Guide minimum estimated values and the actual surface fine fuel quantity in tons per hectare. The blue dots represent the raw data. The black solid line indicates where the points should fall if the Overall Fuel Hazard Guide was accurately and precisely estimating surface fine fuel load for *E. major/C. citriodora* open forest.

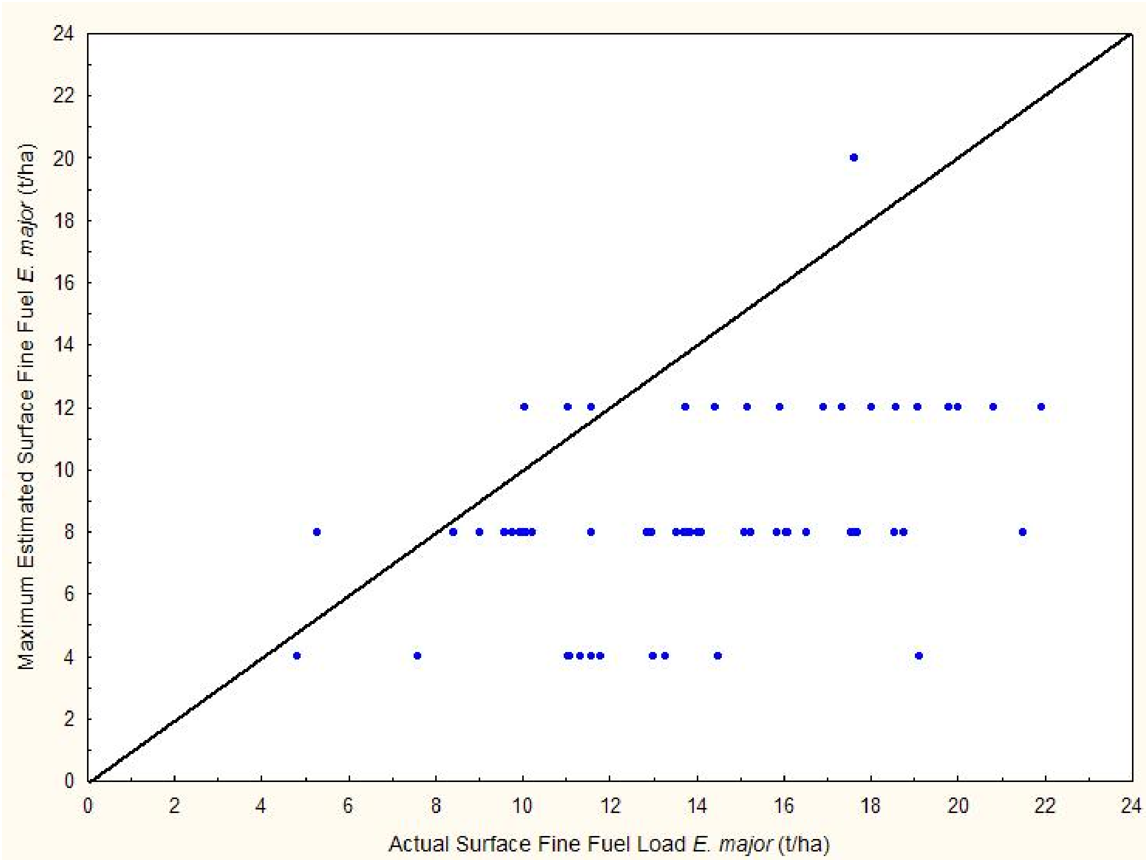

Figure 4.3 Comparison between the Overall Fuel Hazard Guide maximum estimated values and the actual surface fine fuel quantity in tons per hectare. The blue dots represent the raw data. The black solid line indicates where the points should fall if the Overall Fuel Hazard Guide was accurately and precisely estimating surface fine fuel load for *E. major/C. citriodora* open forest.

4.3.2 Eucalyptus racemosa open woodland

Consistent with *E. major/C. citriodora* open forest, the results further emphasise the underestimation of estimated fuel load in comparison to the actual measured fuel load for *E. racemosa* open woodland (Figures 4.4-4.5).

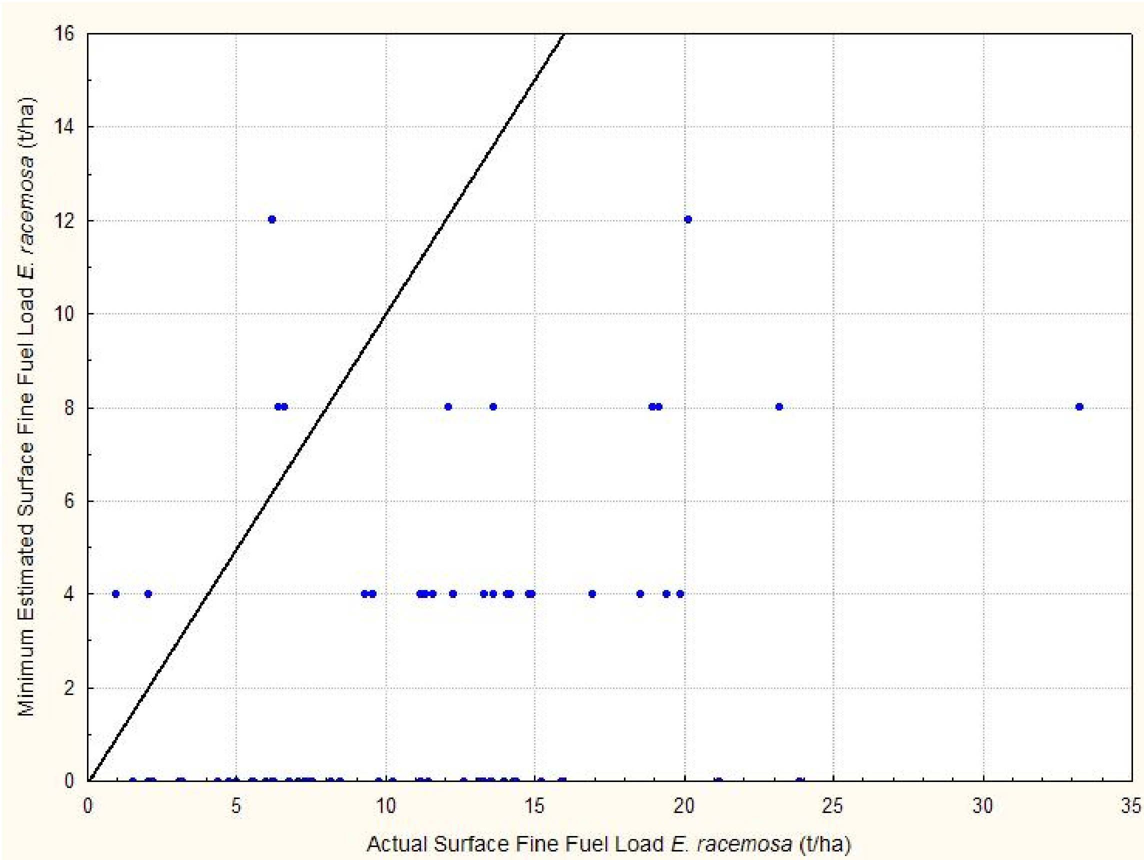

Figure 4.4 Comparison between the Overall Fuel Hazard Guide minimum estimated values and the actual surface fine fuel quantity in tons per hectare. The blue dots represent the raw data. The black solid line indicates where the points should fall if the Overall Fuel Hazard Guide was accurately and precisely estimating surface fine fuel load for *E. racemosa* open woodland.

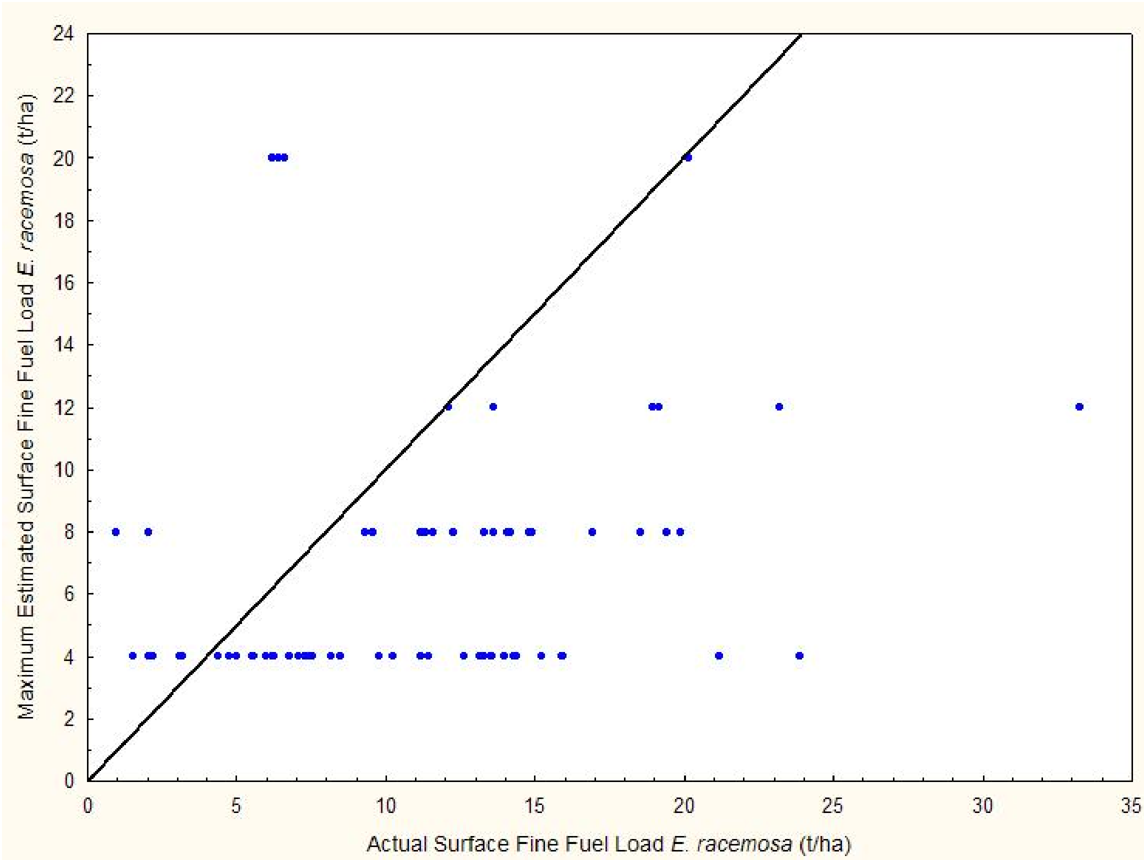

Figure 4.5 Comparison between the Overall Fuel Hazard Guide maximum estimated values and the actual surface fine fuel quantity in tons per hectare. The blue dots represent the raw data. The black solid line indicates where the points should fall if the Overall Fuel Hazard Guide was accurately and precisely estimating surface fine fuel load for *E. racemosa* open woodland.

4.4 Discussion

Fuels, and particularly surface fine fuels, are key contributors to fires, directly affecting fire behaviour and characteristics of fire such as flame height, forward rate of spread and fires ability to spread in both vertical and horizontal directions (Cheney 1981, Keeley & Fotheringham 2001). It is also the only factor that can be manipulated to reduce fire hazard (Conroy 1993). The spatial and temporal arrangement of surface fine fuels is therefore critical to quantify in terms of fire management (McCarthy *et al.* 1999). Methods of classifying the attributes of fuel through the use of basic guides have been required and fire behaviour models, appraisals of suppression difficulty, fuel mapping and fuel hazard assessments have been developed to enable the creation of such guides (Olson 1963, Wilson 1993, Bresnehan 1998, McCarthy *et al.* 1999). Most guides provide

a consistent set of representative average values for fuel characteristics that contribute to fire behaviour (McCarthy *et al.* 1999).

While fuel accumulations models based on scientific research, as above, allow land managers to realistically estimate and predict potential fire behaviour, indirect assessment of fuel loads, via the use of interpretable guides, provides a rapid way of estimating potential fuel load and the associated fire hazard. The Overall Fuel Hazard Guide (McCarthy *et al.* 1999) while providing an excellent tool for estimating fuel loads in eucalypt forests of Victoria and southern New South Wales has shown, in this study, to grossly underestimate surface fine fuel loads. This has very important implications, particularly from a management perspective, given the guides currently widespread use across most of southeast Queensland by land management agencies.

Exact quantities of fuel are rarely required to make decisions regarding prescribed burning or fire exclusion and generally a range such as that given in the Overall Fuel Hazard Guide is enough to provide guidance when deciding appropriate fire management decisions. However, when the fine fuel load estimates were found to be as inaccurate as in the present study, management outcomes may be not only misleading, but potentially dangerous (Bradstock *et al.* 1998). Other studies have also found that using the visual estimation techniques along with fuel depth measurements, while quick and easy to use can still be inaccurate (Bresnehan 1998, Brandis & Jacobson 2003). By underestimating the surface fine fuel hazard, the potential for fire and its subsequent behaviour to occur is also underestimated. The subsequent decisions made in regards to prescribed burning are therefore limited by inaccurate estimations and have the potential to either; prescribed fire in areas that do not require it by overestimating fuel loads, or, as is the case of the present study, not prescribe fires in area (for hazard reduction) due to an underestimation, potentially increasing the risk associated with high surface fine fuel loads and fire hazard.

It would, therefore, be advisable to test the accuracy of the Overall Fuel Hazard Guide in other forest ecosystems within southeast Queensland. Once a definitive appraisal of the

accuracy and precision of the Overall Fuel Hazard Guide is known, the confirmed use, or a ‘correction factor’ could be incorporated into the use of the Overall Fuel Hazard Guide.

While the use of the Overall Fuel Hazard Guide greatly assists in defining the role of each fuel component, for southeast Queensland *E. major/C. citriodora* open forest and *E. racemosa* open woodland ecosystems there is an underestimation of the actual surface fine fuel load. While caution is used in transferring from other ecosystems to that experienced in southeast Queensland in the use of the Overall Fuel Hazard Guide, the results from this aspect of the study emphasize this departure, highlighting the need to develop ecosystem/region specific visual assessment guides. The USA Forest Service produces a number of ecosystem specific litter accumulation, fire behaviour and visual fuel guides. It may be worth considering the development of similar tools for an equally diverse Australian environment.

Chapter 5. Fuel Components

5.1 Introduction

Previously, the importance of determining the fuel load accurately and precisely has been demonstrated. Assessment of the fuel load is dependent on time of assessment and location of assessment (different ecosystems further produce different types of fuels) (Raison *et al.* 1983). This complexity can make it difficult to measure fuel with simple methods as clearly demonstrated in the previous chapter. Fuel components (consisting of leaves, twigs, bark and residue) will differ in their composition, amount and accumulation depending on the vegetation type (refer to Table 5.1) (Brandis & Jacobson 2003).

Fuel beds are structurally complex, varying widely in their physical characteristics and their potential to affect fire behaviour and consequently the efficacy of suppression efforts (Sandberg *et al.* 2001). The structure and composition of both the canopy and understorey (if present) fuels will directly affect the amount and composition of surface fine fuels (Birk 1979, Smith *et al*. 2004). Fine fuels occurring in the mid-storey may contribute to advancing the fire up into the canopy as well as sustaining fires horizontally (Reich *et al*. 2004).

An assessment of the individual fuel components (leaves, twigs (< 6 mm) and bark) is critically important in terms of understanding the structural arrangement of the fuel layers and hence fire advancement and continuity within the landscape (Catchpole 2002). Australian open forests and woodlands consist of fuel deposited predominantly from eucalypts as they are the most prominent vegetation family (Gill 1997). The effects of location, climate, herbivory and natural disturbances on eucalypt communities also causes the fuel loads to be inherently variable and patchy even at the same site (McCarthy 1996).

5.1.1 Leaf

Leaf material forms a major proportion of surface fuel (Table 5.1) (Raison *et al.* 1983). In eucalypts, leaves are generally thin (<0.5 mm) and contain varying amounts of flammable oils and directly as a result of this, are usually consumed first by fire (Gill 1997). Leaf matter generally forms the major proportion of surface fine fuels in Australian eucalypt communities (Tolhurst & Cheney 1999).

5.1.2 Twigs (< 6 mm)

Twigs (less than 6 millimeters) have been shown to form the second key component of surface fuels in most eucalypt communities (Simmons & Adams 1986). The size class of this fuel type allows it to be consumed in the fire-front and actively contributing to a fire's forward rate of spread and intensity (Tolhurst & Cheney 1999). Further, it should also be mentioned that this size class contributes to elevated fuels allowing for fire to spread vertically (Catchpole 2002). Twigs usually form the second largest fraction of surface fine fuel in eucalypt communities (Table 5.1) (Tolhurst & Cheney 1999). Twigs of this size-class have been classed as 'flashy-fuels' (Cheney 1981) and are so-named as the heat required for this fuel component is quite low and similar to that of leaves. Twigs above 6 mm require longer exposure to heat and flame contact in order to assist in fire spread (Luke & McArthur 1978).

5.1.3 Bark

The texture and type of bark is as important as the arrangement and structure of understorey species (McCarthy & Tolhurst 2001). Smooth-barked eucalypt species are significantly less likely to transport flames into the canopy of trees, compared with stringy and fibrous-barked species (Luke & McArthur 1978). Bark also has the potential to spread burning embers and cause spotting (Keeley & Fotheringham 2001). Some Victorian eucalypt species have deep furrowing or long ribbon-like bark that can elevate potential fuel hazard (McCarthy *et al.* 1999). Consequently, Victoria is also known to be the location of some of the most severe and intense fires in Australia (McCarthy & Tolhurst 2001, Catchpole 2002). It is widely acknowledged that south east Queensland

lacks any species which have the same deeply furrowed bark hazard, notable exceptions (such as *E. oreades* aside) (Just 1977, Sandercoe 1990, Watson 2001).

Fuel components vary between species, origin and location, a select summary of fuel-related studies is shown below in Table 5.1

Table 5.1 Comparison of weight in tons per hectare and percentage of components [where recorded] of fuel in Eucalypt forests from other studies (Sources are provided).

Dominant canopy species	Site Location	Leaf	Twigs (<6mm)	Bark	Residue	Source
E. laevopinea *E. viminalis* *E. obliqua*	New England, NSW	1.7 t/ha [51%]	0.7 [22%]	0.5 [14%]	0.4 [11%]	Pressland 1982
E. piluaris *Angophora costata*	Seal Rocks, NSW	N/A [26%]	N/A [35%]	N/A [12%]	N/A [27%]	Fox *et al*. 1979
E. rossii *E. mannifera* *E. macrorhyncha*	Upper Yass Basin, Canberra	0.51 [48%]	0.4 [40.7%]	0.15 [11.2%]	-	Crockford & Richardson 1998
Eucalypt open forest	Not stated	2.02-9.84	0.99-5.22	0.50-2.25	0.33-3.94	Gill 1999
E. obliqua, *E. radiata,* *E. rubida*	Wombat State Forest, VIC	1.9-22.9	0.4-7.7	Inc. in leaf estimate	0.9-8.7	Tolhurst & Kelly 2003
E. obliqua, *E. radiata,* *E. sideroxylon,* *E. polyanthemos,* *E. gonidocalyx*	Victoria, Australia	4.53	4.26	Inc. in leaf estimate	8.93	Simmons & Adams 1986
Jarrah Forest	Western Australia	N/A [53%]	N/A [27%]	Inc. in twig estimate	N/A [20%]	Smith *et al*. 2004
Dry sclerophyll forest	Wombat State Forest, VIC	10.8	2.4	Inc. in leaf estimate	3.1	Tolhurst *et al.* 1992

As the previous studies in Table 5.1 show, leaves regardless of vegetation ecosystems, form the major proportion (in total weight) of surface fuel, then followed by twigs (<6mm), bark and residue respectively (Fox *et al.* 1979, Pressland 1982, Simmons & Adams 1986, Tolhurst *et al.* 1992, Crockford & Richardson 1998, Gill 1999, Tolhurst & Kelly 2003, Smith *et al.* 2004). However, it should be noted these studies were based upon litter accumulation rates, and did not take into account the time since the last fire making comparison of this aspect unlikely. While these other studies have shown the dominance of leaves and small twigs in fuel components, it is important to understand the

relative importance of these fuel components in southeast Queensland forest ecosystems (Watson 2001).

5.2 Methods

Each sample is sorted into the four fuel categories as outlined in section 2.4.4. Each category of fuel is then weighed and recorded. It is to be expected that there will be a weight difference between those recorded for sorting and those for total surface fine fuel weight. This occurs due to the re-absorption of moisture during the sorting process of which can take some considerable time to sort each sample (> 2 hours) (see section 2.5.1 for moisture re-absorption details).

5.2.1 Data analysis

The total contribution to the overall fuel quantity, in tonnes per hectare (t/ha), for each of the fuel components, leaf, twig (< 6 mm) and bark were plotted against time since fire. Trend analyses were performed on each fuel component to determine the role of each fuel component and its change over time.

5.3 Results

5.3.1 Component Characteristics

The proportions of leaves, twigs (< 6 mm) and bark for each of the measured years post-fire. The overall mean (± S.E.) leaf, twig and bark components for the study area was 8.49±1.21 t/ha, 2.38±0.46 t/ha, 6.85±2.02 t/ha respectively for *Eucalyptus racemosa* open woodland. In the *Eucalyptus major / Corymbia citriodora* open forest type the overall mean (± S.E.) leaf, twig and bark components are 9.72±1.19 t/ha, 3.63±0.72 t/ha, 11.21±4.34 t/ha respectively.

The changes in the relative proportions of fuel components illustrated in Figure 5.1, but also including 5.2-5.4 clearly indicate that the leaf matter dominates surface fine fuel load over the entire 22 years of study sites, ranging between 30% (4.5 years post-fire) to 80.4% (15 years post-fire). The twig and bark components displayed no trend, with more

haphazard relationships with time. It should be noted that the normal process of climate, decomposition, microfauna and microbial activity were considered beyond the scope and context of this study. Whilst clearly important in establishing the proportion of fuel, this aspect of the study aimed at providing a snapshot (post-fire) of the fuel component. This provides land managers with a good basis to alter hazard reduction prescriptions (such as mode/type of lighting, timing etc) if there are large changes in relative fuel components over time.

Table 5.2 The relative proportions of leaf, twig and bark fuels for all sites.

		Surface Fine Fuel Fraction		
Time Since Last Fire	**Vegetation Type**	**Mean Leaf (t/ha)**	**Mean Twigs (< 6 mm) (t/ha)**	**Mean Bark (t/ha)**
0.8	W	2.56 (0.68) 34.95%	0.51 (0.13) 9.74%	0.94 (0.28) 1.20%
2	W	4.60 (1.02) 44.25%	2.30 (0.67) 10.40%	8.38 (2.68) 7.12%
3	W	4.48 (0.55) 57.31%	0.96 (0.21) 14.14%	1.83 (0.86) 2.16%
6	W	8.35 (3.25) 43.29%	2.18 (0.66) 31.04%	3.76 (2.05) 25.68%
7	W	8.73 (1.16) 57.57%	2.13 (0.35) 15.38%	11.10 (1.83) 8.15%
8	W	7.12 (0.77) 49.47%	2.81 (0.33) 24.87%	6.74 (1.77) 10.79%
8.5	W	8.58 (0.54) 75.75%	1.78 (0.45) 11.32%	9.03 (4.43) 3.89%
9	W	6.55 (0.90) 52.40%	3.79 (0.61) 36.56%	11.18 (3.51) 6.13%
11	W	6.92 (0.35) 46.62%	4.96 (0.39) 33.72%	8.01 (1.37) 9.30%
11.5	W	13.87 (0.69) 63.61%	4.62 (0.60) 15.72%	9.812 (3.00) 7.08%
15	W	10.00 (1.15) 80.41%	2.57 (0.78) 12.40%	8.04 (1.00) 1.49%
21	W	15.59 (2.70) 65.54%	2.27 (0.33) 15.40%	2.61 (0.47) 7.55%
22	W	12.99 (1.95) 75.19%	1.98 (0.48) 11.51%	7.65 (2.98) 4.36%
4.5	F	8.23 (0.75) 30.16%	5.82 (0.27) 14.05%	20.87 (4.73) 5.11%
10	F	12.28 (2.22) 63.85%	4.46 (1.43) 19.62%	4.80 (2.72) 16.53%
14	F	7.62 (0.72) 62.65%	4.72 (0.90) 27%	4.92 (2.13) 4.99%
14.5	F	8.52 (0.52) 59.37%	2.44 (0.54) 24.93%	16.34 (9.45) 2.15%
18.5	F	11.69 (1.64) 64.94%	1.22 (0.31) 15.86%	5.12 (2.28) 8.88%

Surface Fine Fuel Fraction				
Time Since Last Fire	**Vegetation Type**	**Mean Leaf (t/ha)**	**Mean Twigs (< 6 mm) (t/ha)**	**Mean Bark (t/ha)**
20	F	9.98 (1.31) 65.79%	3.15 (0.87) 21.32%	15.24 (4.74) 5.84%

The proportion of leaves was fairly consistent across all sites over the 22 years measured (Figure 5.1), with the other components more haphazard in proportion over time.

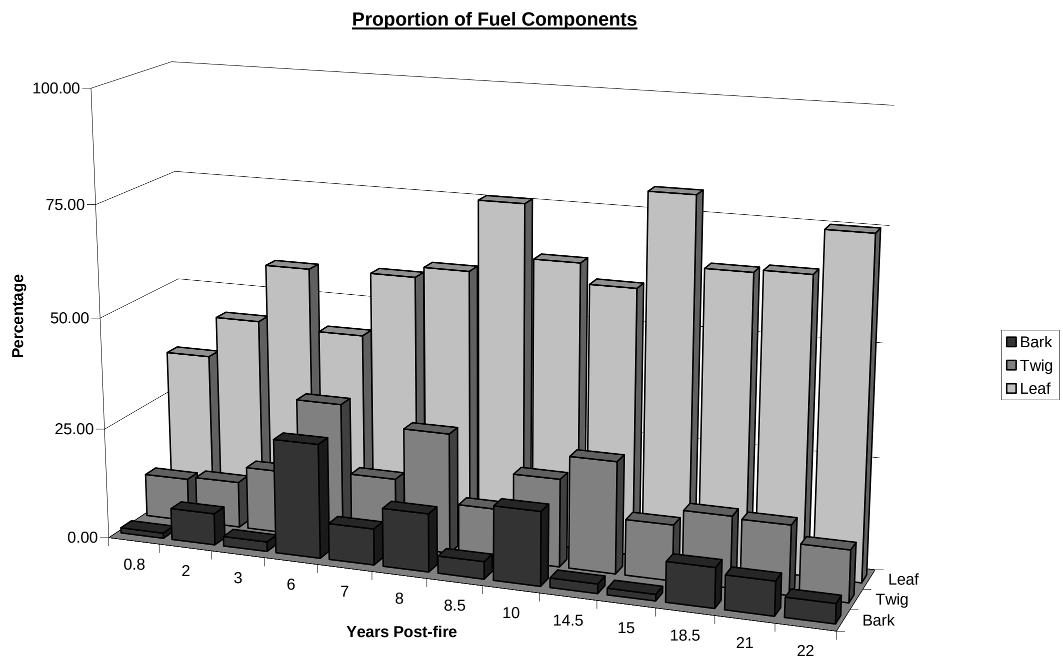

Figure 5.1 Proportions of leaf twig & bark contributing to the surface fine fuel load for each time since fire.

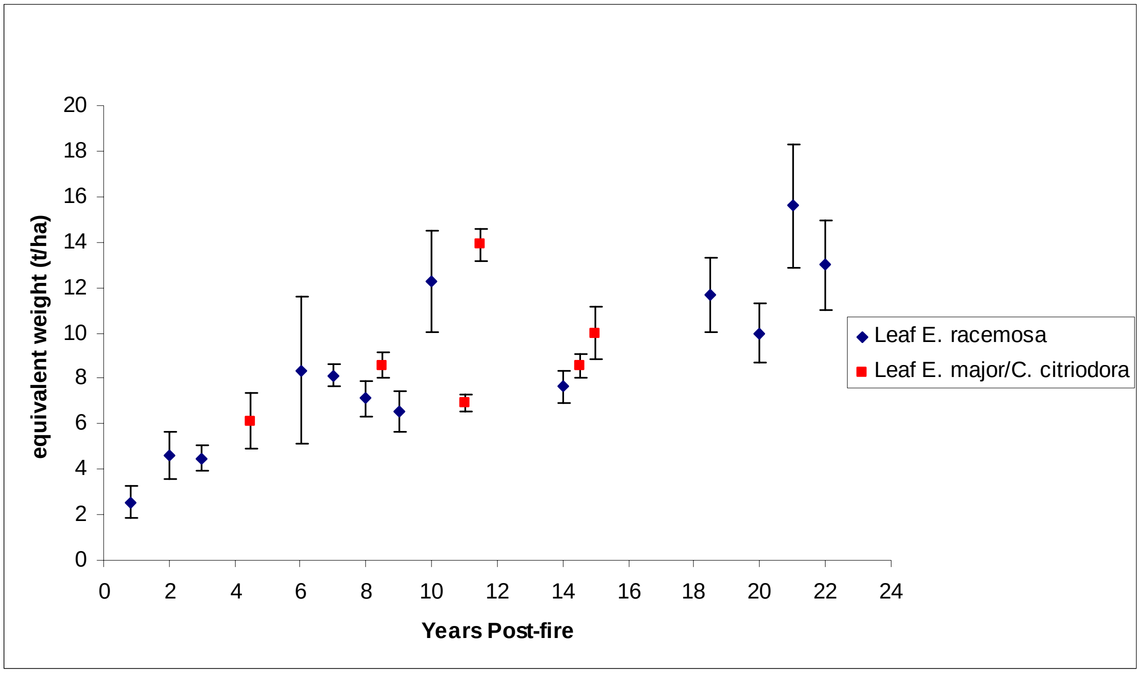

Figure 5.2 Leaf fraction of surface fine fuel for *E. racemosa* open woodland (blue dots) and *E. major / C. citriodora* open forest (red dots) including the standard error for each.

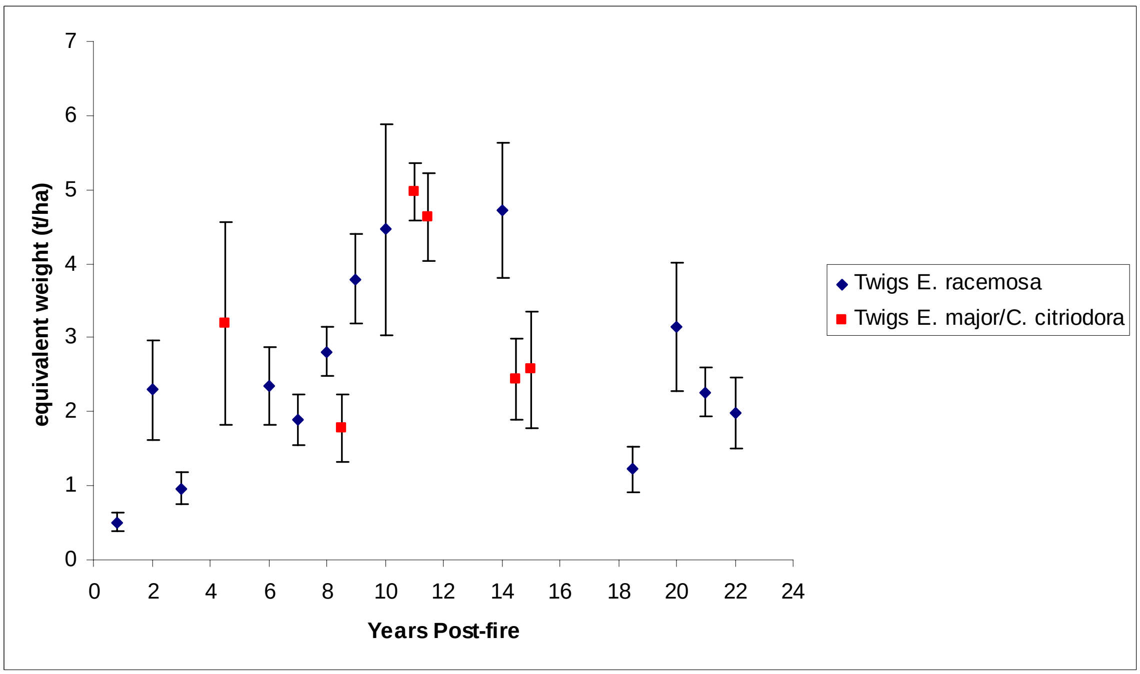

Figure 5.3 Twig fraction of surface fine fuel for *E. racemosa* open woodland (blue dots) and *E. major / C. citriodora* open forest (red dots) including the standard error for each.

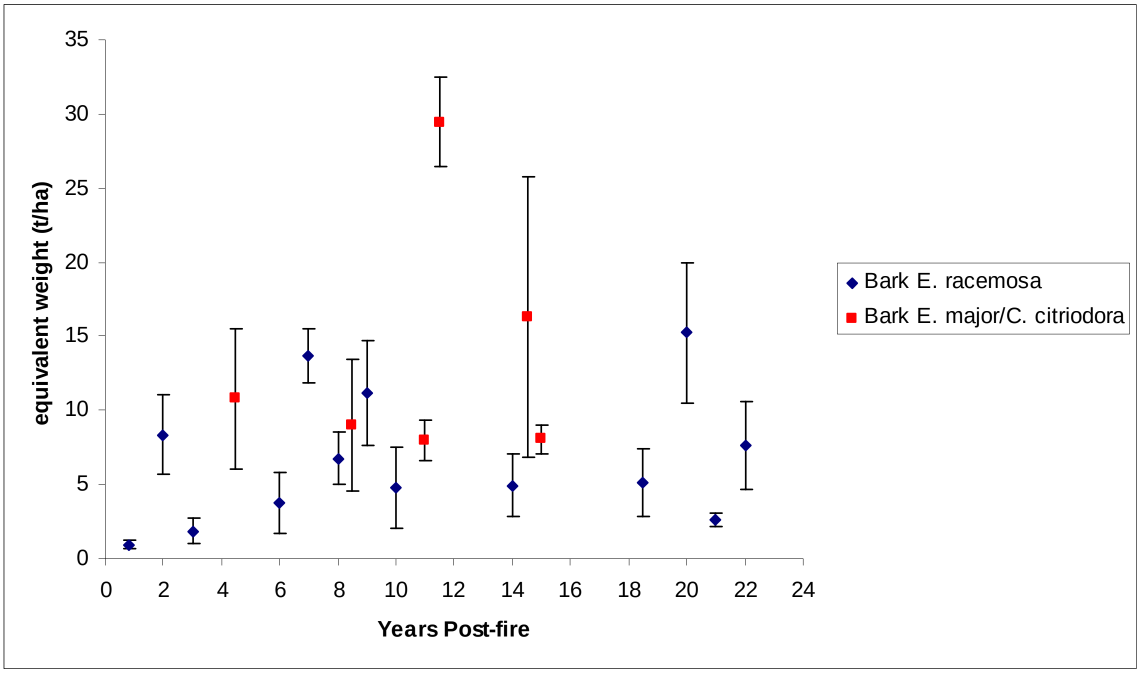

Figure 5.4 Bark fraction of surface fine fuel for *E. racemosa* open woodland (blue dots) and *E. major / C. citriodora* open forest (red dots) including the standard error for each.

5.3 Discussion

Understanding the change in fuel components over time is important in order to accurately prescribe appropriate hazard reduction operations. If a particular fuel component changes dramatically over time, this could adversely affect the fire behaviour, causing unforeseen problems and exacerbate suppression difficulties. The combination of fuel components that comprise the surface fine fuel layer will affect the burning properties of this layer (Burrows 2001). Knowledge of how the fuel components change over time allows for the determination and calculation of characteristics of fire behaviour such as potential rates of spread, intensity and interpreting the potential impact of a fire (Burrows 2001).

An understanding of how the surface fine fuel layer changes over time may provide an indication of how the flammability will change. In studies conducted in the Jarrah forests of Western Australia, Burrows (2001) highlights that the twig proportion of surface fuel steadily increases until 10-15 years post-fire at which time, stabilisation then occurs. Burrows (2001) concludes that changing surface fuel layers and changing proportions of individual fuel components directly affects flammability and that the quantity of fuel may

not be adequate to determine the ‘combustion properties’ and hence fire hazard alone. Other studies (Simmons & Adams 1986) also conclude that by gaining an understanding of the how fine fuels accumulate allows for a number of potential benefits in determining fire behaviour such as; estimating steady state fine fuel levels, assessing the effectiveness of prescribed burning, and assist in the development of fire interval guidelines for different vegetation types.

This study provides an indication about how the quantity of each component changes over time and how the relative proportions of each contribute to the surface fine fuel layer. It is comparable with that of other studies which have shown that leaf matter remains the dominant proportion, contributing to half of the surface fine fuel over time (Pressland 1982, Tolhurst & Kelly 2003, Smith *et al.* 2004). The leaf component of the fuel layer seems to reach equilibrium after 7-8 years post fire, again, comparable to other studies (Pressland 1982, Tolhurst & Kelly 2003, Smith *et al.* 2004). Small twigs and bark, whilst important contributors to fuel hazard displayed less noticeable trends over the fire histories of the sites examined in the study. Further, the results indicate that the operational requirements for hazard reduction to reduce fuel loads can remain fairly consistent regardless of the time since last fire.

This study has provided an outline for baseline knowledge for fuel components in comparable regions in southeast Queensland. Further study of this nature across vegetation types and confirmation across a broader geographical range is warranted in the future.

Chapter 6. General Conclusions

Fires, whether wild or prescribed, exhibit a dominating influence on the Australian landscape. Land managers are required to develop and implement fire management plans in order to contend with the complex requirements of life and property protection as well as the ecological needs of the fire-adapted landscape. Land managers in southeast Queensland rely upon fuel growth models and hazard assessment guides developed in other regions of Australia and the reliability of these guides has not been thoroughly tested.

This study examined the surface fuel component of forested landscapes (*Eucalyptus racemosa* and *E. major*/*Corymbia citriodora* overstoreys) in Redland Shire Council of southeast Queensland. Surface fine fuels are considered to be the most important fuel component in determining the forward rate of spread, fireline intensity and propagation of canopy fires. Reliable negative exponential fuel growth curves were calculated for the *E. racemosa* open woodland but reliable fuel growth curves were not able to be calculated for the *E. major/C. citriodora* open forest type due to a lack of appropriate sites early post-fire or long time since fire. Further, multiple linear regression showed highly significant predictors of potential fuel load for *E. racemosa* open woodlands, with fuel depth, foliage projected cover and time since fire as very reliable predictors of the actual fuel mass. This regression model should be tested in other comparable regions in southeast Queensland in order to test the robustness of this model. Further, the key outcome from this aspect of the study provides land managers with a relatively simple model to assist in predicting the potential fuel loadings of forested landscapes. This helps land managers prioritise mitigation efforts as well as maintaining the fine balance with the ecological needs of the landscape.

The Overall Fuel Hazard Guide was developed in Victoria and aimed at providing an easy-to-follow visually based non-intrusive and time-saving method of assessing potential fuel-loads across a number of different landscapes. This guide has been widely used among land management agencies in southeast Queensland. The second objective of

this study was to examine the efficacy and accuracy of the use of the Overall Fuel Hazard Guide, comparing the estimated results with the actual surface fine fuel loadings. The results indicated a highly significant underestimation in both the minimum and maximum fine fuels as determined by the Overall Fuel Hazard Guide, in both *E. racemosa* open woodlands and *E. major/C. citriodora* open forest. Whilst the Overall Fuel Hazard Guide provides a good indicator of contributors to the overall fuel load, caution should be used due to the consistent underestimation of the actual surface fuel loads.

Leaves, twigs, bark and residue comprise the majority of the components of fuel. The final aspect of this study examined the changes in proportion of these fuel characteristics over time (from 0.8 - 22 yrs post-fire). Leaves remained the major component of the fuel load over this time frame, reaching equilibrium approximately 7-8 years post-fire. The bark and twig components showed no useful trends over this timeframe. From an operational perspective, this result shows that land managers do not need to drastically alter their prescribed burning regimes due to changes in the composition of the fuel load.

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Appendices

Appendix 1 Copy of Overall Fuel Hazard Guide

Fire Research

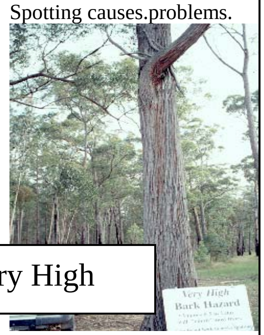
Overall Fuel Hazard Card (Sept 2000)

Assessing Fuel Component Hazard Ratings

(Overall = Bark + Elevated + Surface)

Assess levels of Bark, Elevated and Surface Fine Fuel Hazard as follows.

Bark Hazard Rating

Low Moderate	No flammable bark Little bark to add to fire behaviour. 	Very High	Significant loose bark. Fires will climb most trees. Spotting causes.problems. 
High	Some loose fibrous bark. Some fire will climb trees. Some spotting. 	*Extreme*	Large amounts of loose bark. Fires climb all trees. Severe spotting. 

Elevated Fuel Hazard Rating

Description	
No elevated fuel. *"Easy to walk through in any direction."*	Low

Little elevated fuel. *"Easy to walk through, but vegetation does brush legs occasionally."* **Moderate**	
Some scattered elevated fuel. *"Moderately easy to walk through, but brush against or step over vegetation most of the time."* 0.5 m high. 0 -20% dead. Patchy increase in fire behaviour **High**	
Significant elevated fuel. *"Difficult to walk through. Need to carefully select path and step high."* 20 - 30% dead. 0.5 to 1.5 m high. Fuel elements mostly 2mm or less. Elevated fuel mostly determines fire behaviour. ***Very High***	
Taller, dense elevated fuel. *"Very difficult to see where you are going. Need to use arms to push through vegetation."* 30 - 50% dead. 2.0+ m high. Fuel elements mostly 2mm or less. Elevated fuel completely determines fire behaviour. ***Extreme***	

Surface Fine Fuel Hazard Rating System based on

Litter Bed Height (measure with gauge)

Surface Fine Fuel Hazard	***Low***	***Mod***	***High***	***Very High***	*Extreme*
Litter Bed Height (mm)	<15	15-25	25-35	35-50	>50
Equivalent Surface Load (t/ha)	<4	4-8	8-12	12-20	>20

Combining Bark, Elevated and Surface Fine Fuel Hazards to give an Overall Fuel Hazard for a site:

Table 1. Bark Hazard: ***Low or Moderate***

Surface Fine Fuel Hazard

		L	**M**	**H**	**VH**	**E**
	L	L	M	M	H	H
Elevated	**M**	L	M	M	H	H
Fuel	**H**	L	M	H	VH	VH
Hazard	**V**	VH	VH	VH	VH	VH
	E	E	E	E	E	E

Table 2. Bark Hazard: ***High***

Surface Fine Fuel Hazard

		L	M	H	VH	E
	T	L	M	H	H	H
Elevated	M	L	M	H	H	H
Fuel	H	L	H	H	VH	VH
Hazard	V	VH	VH	VH	VH	E
	E	E	E	E	E	E

Table 3. Bark Hazard: *Very High/Extreme*

Surface Fine Fuel Hazard

		L	M	H	VH	E
	T	M	VH	VH	VH	E
Elevated	M	M	VH	VH	E	E
Fuel	H	M	VH	E	E	E
Hazard	V	E	E	E	E	E
	E	E	E	E	E	E

Equivalent Fuel Loads (t/ha) for given Hazard ratings

(Insert total of components into McArthur Meter for predictions of forward rate of spread and flame height)

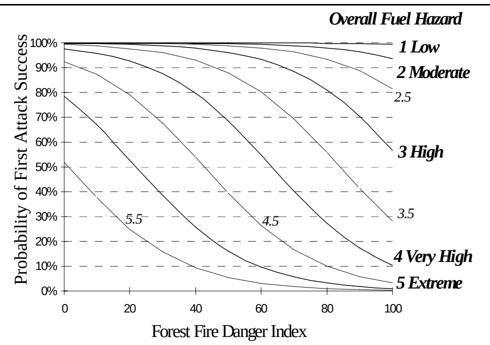
Fuel	***Low***	***Mod***	***High***	***V High***	***Extreme***
Bark	0	0	2	5	7
Litter/ Surface	2	6	10	16	20
Elevated	0	0	2	6	10

e.g. *High* Bark ***High*** Surface ***V. High*** Elevated
2 + 10 + 6 = 18 t/ha **Overall**

Suggested Overall Hazard levels for Fuel Management Zones

FMZ 1 (P1) - *Moderate*
FMZ 2 (P2) - *High*
FMZ 3 (P3) - *High* on 50% of total area. (i.e. other 50% may be higher)

Probability of First Attack Success



This graph is based on data from Fire Research Report No.45. There were no first attack failures on ***High*** Overall sites, but Extended First Attack (15+ men, big dozers, big tankers, aircraft etc.) was required on some Overall ***High*** sites at higher FDIs

For further information:Fire Research Officers Orbost 03 51541208 , Creswick 03 53214181.
Refs : Fire Research Reports No. 45 & 47. Prepared by : Greg McCarthy Sept 2000.

Appendix 2 Data Sheets

Fuel Load Sample Weight Data Sheet

Site Name/ Location.. Date/ Time...................

Field Officer/s..

Sample	Initial Weight (g)	Weight 1	Weight 2	Weight 3	Weight 4	Final Dry Weight

Other comments

………………………………………………………………………………………
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Overall Fuel Hazard Data Sheet	
Location	
Team	
Date	

Site						
Sample	1	2	3	4	5	6
Surface Fine Fuel (L/M/H/VH/E)						
Near Surface Fuel Adjust Y/N						
Elevated Fuel Hazard (L/M/H/VH/E)						
Bark Hazard (L/M/H/VH/E)						
Overall Fuel Hazard (L/M/H/VH/E)						
Estimated Fuel Load T/ha						
Site						
Sample	1	2	3	4	5	6
Surface Fine Fuel (L/M/H/VH/E)						
Near Surface Fuel Adjust Y/N						
Elevated Fuel Hazard (L/M/H/VH/E)						
Bark Hazard (L/M/H/VH/E)						
Overall Fuel Hazard (L/M/H/VH/E)						
Estimated Fuel Load T/ha						
Site						
Sample	1	2	3	4	5	6
Surface Fine Fuel (L/M/H/VH/E)						
Near Surface Fuel Adjust Y/N						
Elevated Fuel Hazard (L/M/H/VH/E)						
Bark Hazard (L/M/H/VH/E)						
Overall Fuel Hazard (L/M/H/VH/E)						
Estimated Fuel Load T/ha						

Date:……………… **Time start:…………** **finish:…………..** **Loc/ Site:……………………………** **Team:………………………………**

Weather:……………………………………… **Last Burn:………………………P or W..** **GPS: E……………………S……………………………**

Vegetation Data Plot 1	**Plot 2**	**Plot 3**	**Plot 4**	**Plot 5**
Canopy				
Canopy Photo No.				
Understorey				
Ground Cover				
Est. FH				
GPS E				
GPS S				
Topography				
Other notes (weeds/soils)				

Appendix 3 Species List

Eucalyptus major/Corymbia citriodora – Open Forest

Scientific Name	**Common Name**
Acacia auloacocarpa	Early black wattle
Acacia concurrens	Late black wattle
Allocasuarina torulosa	Forest she-oak
Allocasuarina littoralis	Black she-oak
Alphitonia excelsa	Red ash, Soap tree
Corymbia intermedia	Pink bloodwood
Corymbia trachyphloia	Brown bloodwood
Corymbia citriodora	Spotted gum
Eucalyptus fibrosa	Broad-leaved Red Ironbark
Eucalyptus major	Grey gum
Eucalyptus microcorys	Tallowwood
Eucalyptus seeana	Narrow-leaved Red gum
Eucalyptus siderophloia	Ironbark
Lophstemon confertus	Brush box
Lophostemon suaveolens	Swamp mahogany
Acacia perangusta	Eprapah wattle
Hibbertia stricta	Erect Guinea Flower
Hovea acutifolia	Poined-leaved hovea
Jacksonia scoparia	Dogwood, native broom
Leptospermum polygalifolium	Wild may
Pultenea euchila	Orange flowered pultenea
Pultenea villosa	Hairy bush pea
Cymbopogon refractus	Barb-wire grass
Ottochloa gracillima	Slender shade grass
Goodenia rotundifolia	A fan flower
Dianella caerulea	Flax lilly, Blue-berry lilly
Lomandra longifolia	Long-leaved matrush
Eustrephus latifolius	Wombat berry

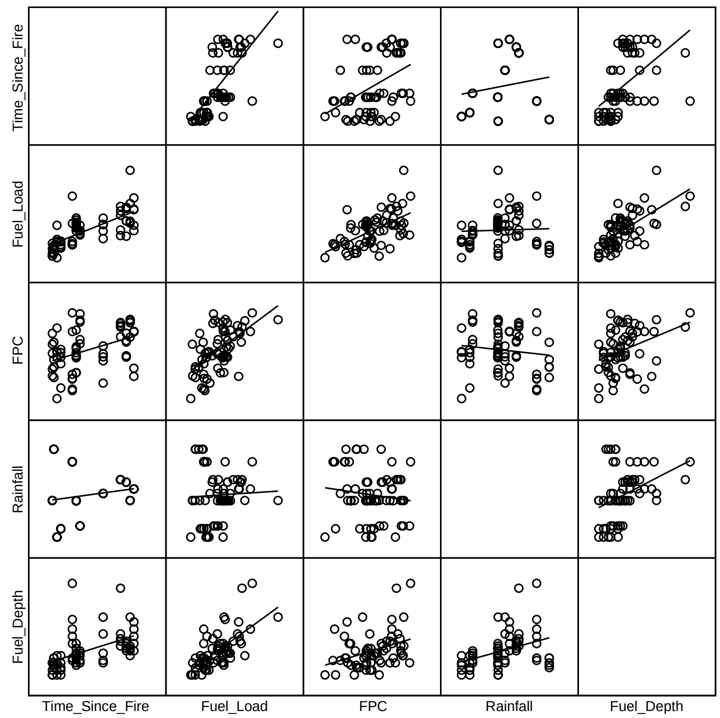
Eucalyptus racemosa – Open Forest

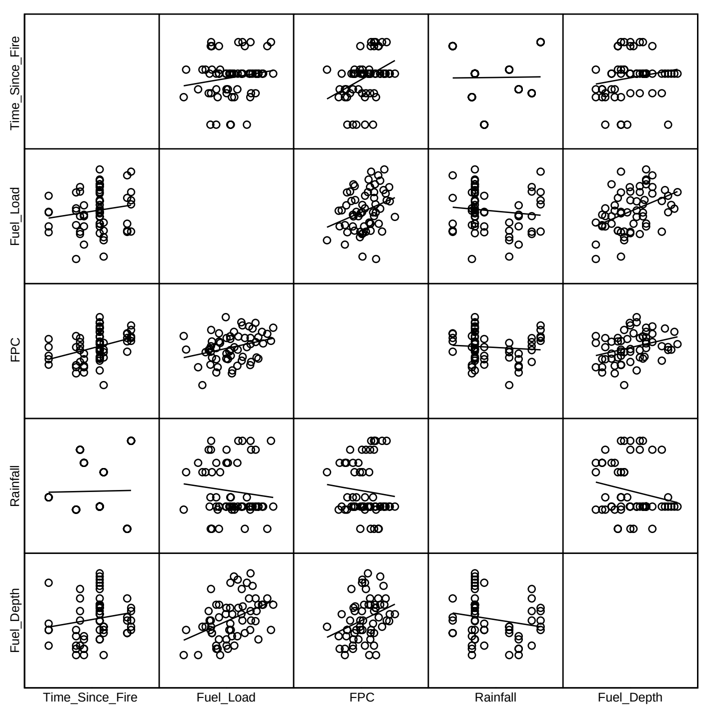
Scientific Name	**Common Name**
Acacia concurrens	Late black wattle
Acacia leiocalyx	
Allocasuarina littoralis	Black she-oak
Alphitonia excelsa	Red ash, Soap tree
Angophora woodsiana	Smudgee
Corymbia trachyphloia	Brown bloodwood
Eucalyptus fibrosa	Broad-leaved Red Ironbark
Eucalyptus racemosa	Scribbly gum
Eucalyptus seeana	Narrow-leaved Red gum

Eucalyptus siderophloia	Ironbark
Eucalypytus tereticomis	Qld blue gum
Glochidion ferdinandii	Cheese wood tree
Lophstemon confertus	Brush box
Lophostemon suaveolens	Swamp mahogany
Melaleuca quinquennervia	Paper-barked tea tree
Acacia falcate	
Banksia spinulosa var collina	Golden candles
Elaeocarpus reticulatus	Blueberry ash
Hakea florulenta	A hakea
Hibbertia stricta	Erect Guinea Flower
Hovea acutifolia	Poined-leaved hovea
Jacksonia scoparia	Dogwood, native broom
Leptospermum polygalifolium	Wild may
Melaleuca sieberi	A tea tree
Pultenea villosa	Hairy bush pea
Westringia eremicola	Native westringia
Xanthorrhoea fulva	Grass tree
Hibbertia scandens	Guinea flower, snake vine
Cymbopogon refractus	Barb-wire grass
Ottochloa gracillima	Slender shade grass
Themeda triandra	Kangaroo grass
Goodenia rotundifolia	A fan flower
Viola hederacea	Native violet
Junsens usitatus	Common Rush
Dianella caerulea	Flax lilly, Blue-berry lilly
Lomandra longifolia	Long-leaved matrush
Eustrephus latifolius	Wombat berry
Hardenbergia violacea	False sarsaparilla

Appendix 4 Statistical Output

Scatterplot matrices from SPSS output for linear regression models for *E. racem*osa open woodland and *E.major/C. citriodora* open forest respectively.





Appendix 5 Raw Data

E. major/C. citriodora

Sample	Fuel Age	Leaf	Twig	Bark	Actual Litter Load (t/ha)	Foliage Projected Cover	Rainfall average mm	Estimated Fuel Load Max	Estimated Fuel Load Min	Litter Depth
HT, T1P1	4.5	9.4192	5.394	25.56	16.9	52.49	86.42	12	8	32
HT, T1P2	4.5	7.042	6.2424	16.18	13.73	57.62	86.42	8	4	19
HT, T1P3	4.5	9.3128	2.3184	1.296	13.83	46.95	86.42	8	4	17
HT, T1P4	4.5	7.7644	2.1684	0.776	9.93	41.24	86.42	8	4	17
HT, T1P5	4.5	7.2276	0.0296	7.468	11.04	44.73	86.42	4	0	12
Emu, T2P1	8	3.106	2.334	4.944	4.83	59.51	77.27	4	0	9
Emu, T2P2	8	11.7416	2.9748	15.156	17.54	41	77.27	8	4	17
Emu, T2P3	8	9.0224	3.2772	7.76	14.04	35.73	77.27	8	4	15
Emu, T2P4	8	6.6252	3.9976	12.3	11.31	39.7	77.27	4	0	11
Emu, T2P5	8	7.6476	4.636	15.256	14.49	52.4	77.27	4	0	12
FRd, T1P1	8.5	7.8404	0.6448	26.372	17.7	43.02	121.71	8	4	20
FRd, T1P2	8.5	9.6064	1.4148	6.048	13.01	58.23	121.71	4	0	12
FRd, T1P3	8.5	10.0364	2.088	7.024	18.58	55.69	121.71	12	8	27
FRd, T1P4	8.5	7.1596	3.3248	3.844	9.59	50.53	121.71	8	4	23
FRd, T1P5	8.5	8.2384	1.41	1.876	10.04	53.05	121.71	12	8	30
Emu, T1P1	9	6.8584	3.8268	10.772	12.98	48.31	111.98	4	0	14
Emu, T1P2	9	4.11	3.7964	3.716	7.58	39.68	111.98	4	0	9
Emu, T1P3	9	5.9076	2.8468	9.336	15.08	40.57	111.98	8	4	15
Emu, T1P4	9	8.0844	0.2756	11.716	13.27	44.82	111.98	4	0	11
Emu, T1P5	9	6.0656	2.198	2.704	11.06	36.31	111.98	4	0	11
WMTC, T1, P1	11	5.596	5.7244	1.928	19.1	45.11	79.5	4	0	14
WMTC, T1, P2	11	5.9564	9.7276	17.764	18.55	67.9	79.5	8	4	19.8
WMTC, T1, P3	11	8.4688	7.426	5.208	18.75	45.91	79.5	8	4	23
WMTC, T1, P4	11	6.3328	5.9724	9.24	15.84	68.23	79.5	8	4	22
WMTC, T1, P5	11	3.2744	5.296	6.196	21.93	64.79	79.5	12	8	25
WMTC, T2, P1	11	8.0244	7.9212	8.684	19.79	62.12	79.5	12	8	28

WMTC, T2, P2	11	6.8088	6.7112	9.412	16.1	46.24	79.5	8	4	24
WMTC, T2, P3	11	4.2452	5.9932	3.256	11.05	51.89	79.5	12	8	28
WMTC, T2, P4	11	6.7796	6.9336	6.104	17.6	54.33	79.5	20	12	35
WMTC, T2, P5	11	8.3144	4.2148	1.968	17.99	64.29	79.5	12	8	31
WMTC, T3, P1	11	6.3112	2.0836	9.936	15.91	43.8	79.5	12	8	30
WMTC, T3, P2	11	8.6724	4.2208	6.76	19.09	58.76	79.5	12	8	25
WMTC, T3, P3	11	4.8844	2.3396	2.924	11.59	55.94	79.5	12	8	25
WMTC, T3, P4	11	5.3156	3.5892	3.152	9.77	51.23	79.5	8	4	20
WMTC, T3, P5	11	8.228	6.266	5.896	14.43	62.19	79.5	12	8	34
WMTC, T4, P1	11	6.2788	2.5776	6.82	11.56	55.88	79.5	4	0	14
WMTC, T4, P2	11	6.3352	5.4428	6.476	12.97	45.14	79.5	8	4	24
WMTC, T4, P3	11	8.1948	3.4256	2.94	17.32	65.65	79.5	12	8	27
WMTC, T4, P4	11	6.8132	5.898	33.952	15.15	50.79	79.5	12	8	33
WMTC, T4, P5	11	12.342	3.8044	19.18	20	54.74	79.5	12	8	25
WMTC, T5, P1	11	7.81	5.6556	8.572	13.69	59.32	79.5	8	4	24
WMTC, T5, P2	11	6.0116	3.9364	4.152	12.86	71.51	79.5	8	4	22
WMTC, T5, P3	11	7.6348	3.4876	6.516	13.75	50.62	79.5	12	8	32
WMTC, T5, P4	11	7.356	3.1164	5.944	14.11	37.64	79.5	8	4	22
WMTC, T5, P5	11	7.022	2.3276	7.376	13.54	49.63	79.5	8	4	17
SUM, T2P1	11.5	5.1356	0.6136	15.816	11.79	55.16	104.99	4	0	9
SUM, T2P2	11.5				9	49.25	104.99	8	4	18
SUM, T2P3	11.5	5.4836	1.3536	6.648	10.23	45.81	104.99	8	4	16
SUM, T2P4	11.5				8.4	28.3	104.99	8	4	18
SUM, T2P5	11.5	3.25	2.656	6.972	5.29	50.89	104.99	8	4	17
SUM, T1P1	14.5	9.9272	3.8412	48.032	20.8	60.88	63	12	8	27
SUM, T1P2	14.5	8.8056	3.0036	6.516	16.5	58.29	63	8	4	16
SUM, T1P3	14.5				10	49.51	63	8	4	20
SUM, T1P4	14.5	8.2444	1.7284	5.068	11.57	61.2	63	8	4	21
SUM, T1P5	14.5	7.1084	1.1748	5.74	10.22	56.07	63	8	4	16
FRd, T2P1	15	6.6492	5.5504	4.796	10.07	63.34	128.33	8	4	18
FRd, T2P2	15	10.3648	2.3716	7.384	15.25	59.17	128.33	8	4	24
FRd, T2P3	15	10.6712	0.9896	7.724	16.04	66.26	128.33	8	4	20
FRd, T2P4	15	13.5784	2.2228	9.988	21.5	56.38	128.33	8	4	17

FRd, T2P5	15	8.7144	1.6984	10.312	17.6	58.26	128.33	8	4	23

E. racemosa

Sample	Fuel Age	Leaf	Twig	Bark	Actual Litter Load (t/ha)	Foliage Projected Cover	Rainfall average mm	Estimated Fuel Load Max	Estimated Fuel Load Min	Litter Depth
GGR, T1P1	0.8	4.9452	0.4872	0.152	6.74	38.31	98.13	4	0	7
GGR, T1P2	0.8	3.0068	0.6492	1.208	4.77	54.89	98.13	4	0	10
GGR, T1P3	0.8	0.9672	0.8816	0.42	2.07	45.92	98.13	4	0	5
GGR, T1P4	0.8	1.7476	0.1092	1.444	2.19	19.67	98.13	4	0	10
GGR, T1P5	0.8	2.1132	0.4048	1.484	3.1	25.25	98.13	4	0	5
CSTW, T2P1	1.2				3.2	27.22	151.33	4	0	8
CSTW, T2P2	1.2				5.6	33.2	151.33	4	0	12
CSTW, T2P3	1.2				6	47.53	151.33	4	0	10
CSTW, T2P4	1.2				4.4	26.79	151.33	4	0	9
CSTW, T2P5	1.2				3.2	18.24	151.33	4	0	12
JH, T1P1	2	7.5952	0.4104	21.588	13.26	59.36	60.16	4	0	10
JH, T1P2	2	4.9924	4.61	7.072	8.15	39.82	60.16	4	0	7
JH, T1P3	2	4.3108	1.9008	7.548	7.51	39.31	60.16	4	0	13
JH, T1P4	2	4.908	2.3608	5.436	7.06	34.79	60.16	4	0	9
JH, T1P5	2	1.1916	2.2132	0.252	1.51	0.82	60.16	4	0	5
McM, T2P1	3	5.7384	0.5296	5.076	7.27	35.07	68.78	4	0	7
McM, T2P2	3	5.8352	0.4076	1.544	7.52	38.96	68.78	4	0	10
McM, T2P3	3	3.208	1.2468	0.588	5.02	41.66	68.78	4	0	13
McM, T2P4	3	3.6884	1.1276	1.724	6.26	29.69	68.78	4	0	8
McM, T2P5	3	3.9312	1.5024	0.232	5.52	9.61	68.78	4	0	5
B11, T1, P1	6	0.9332	0.008	0.148	0.971		138.3	8	4	18
B11, T1, P2	6	2.0564	2.4748	0	2.064		138.3	8	4	21
B11, T1, P3	6	9.3652	3.9008	2.624	12.1	26.59	138.3	12	8	24
B11, T1, P4	6	18.8716	2.98	11.16	23.89	72.05	138.3	4	0	11
B11, T1, P5	6	10.5296	1.526	4.848	13.99	56.45	138.3	4	0	12
CSTW, T1P1	6				6.2	20.94	138.3	4	0	11
CSTW, T1P2	6				7.4	17	138.3	4	0	12

CSTW, T1P3	6				6.2	8.75	138.3	20	12	34
CSTW, T1P4	6				6.6	7.43	138.3	20	8	56
CSTW, T1P5	6				6.4	17.55	138.3	20	8	57
JH, T2P1	7	9.8172	1.0976	0.996	14.4	43.73	97.86	4	0	14
JH, T2P2	7	9.2076	1.1648	15.868	15.95	57.59	97.86	4	0	12
JH, T2P3	7	10.22	0.9916	9.852	14.29	35.22	97.86	4	0	14
JH, T2P4	7	9.2512	2.1584	13.808	12.65	35.27	97.86	4	0	10
JH, T2P5	7	8.686	1.0076	14.132	15.22	42.37	97.86	4	0	14
McM,T1P1	7	7.0732	2.2232	10.268	12.27	22.15	97.86	8	4	18
McM,T1P2	7	7.8524	3.7568	20.18	13.62	36.68	97.86	8	4	16
McM,T1P3	7	6.6152	3.3736	19.544	13.52	22.43	97.86	4	0	9
McM,T1P4	7	6.4784	2.6068	19.232	13.15	34.69	97.86	4	0	13
McM,T1P5	7	6.1444	0.598	12.944	11.24	38.92	97.86	8	4	16
B10, T1P1	8				15.2		71.65	99	99	99
B10, T1P2	8				16		71.65	99	99	99
B10, T1P3	8				12.4		71.65	99	99	99
B10, T1P4	8				16.2		71.65	99	99	99
B10, T1P5	8				15.4		71.65	99	99	99
BBR, T1P1	8	6.1476	2.7284	2.656	13.28	64.36	71.65	4	0	14
BBR, T1P2	8	4.6604	1.2816	1.704	10.26	65.87	71.65	4	0	13
BBR, T1P3	8	5.8564	3.108	2.78	9.76	71.2	71.65	4	0	10
BBR, T1P4	8	7.5676	2.3136	4.34	11.46	49.7	71.65	4	0	15
BBR, T1P5	8	8.818	1.4092	0.528	11.15	46.31	71.65	4	0	11
B11, T2, P1	9	9.912	5.7348	11.176	13.12	55.62	92.63	99	99	99
B11, T2, P2	9	2.7188	4.7168	9.288	6.97	47.21	92.63	99	99	99
B11, T2, P3	9	2.422	4.594	1.584	3.99	36.04	92.63	99	99	99
B11, T2, P4	9	9.2176	2.814	10.696	16.02	26.25	92.63	99	99	99
B11, T2, P5	9	10.1672	7.108	40.848	18.97	30.75	92.63	99	99	99
B13, T1, P1	10	13.6296	1.112	14.892	17.97	69.06	76.58	99	99	99
B13, T1, P2	10	8.7616	1.4648	0	9.04	38.22	76.58	99	99	99
B13, T1, P3	10	16.228	8.6104	0.112	18.44	55.11	76.58	99	99	99
B13, T1, P4	10	17.1912	6.1992	5.26	18.83	60.89	76.58	99	99	99
B13, T1, P5	10	5.6088	4.9132	3.724	7.45	58.45	76.58	99	99	99

Well, T2P1	14	8.8484	2.5624	1.756	11.19	38.02	105.36	8	4	22
Well, T2P2	14	9.1984	3.3812	12.956	15.88	44.43	105.36	4	0	14
Well, T2P3	14	7.7384	6.1044	5.592	13.6	32.06	105.36	12	8	29
Well, T2P4	14	5.1352	7.456	1.644	8.46	13.61	105.36	4	0	11
Well, T2P5	14	7.1904	4.0928	2.676	13.57	35.44	105.36	4	0	10
Ent, T1P1	18.5	15.5716	2.0544	9.268	20.15	60.24	119.74	20	12	41
Ent, T1P2	18.5	13.8124	1.5028	3.12	18.53	61.38	119.74	8	4	22
Ent, T1P3	18.5	13.156	1.3716	1.452	16.95	52.2	119.74	8	4	19
Ent, T1P4	18.5	9.442	0.988	0.032	11.58	63.99	119.74	8	4	17
Ent, T1P5	18.5	6.4708	0.1964	11.74	9.55	63.17	119.74	8	4	20
Well, T1P1	20	6.296	5.7168	6.624	9.32	36.37	117.18	8	4	16
Well, T1P2	20	10.8608	2.1416	31.536	19.89	47.67	117.18	8	4	18
Well, T1P3	20	10.0676	4.72	7.656	14.89	48.92	117.18	8	4	17
Well, T1P4	20	14.1772	1.9168	10.14	19.43	55.05	117.18	8	4	19
Well, T1P5	20	8.5176	1.2476	20.252	14.89	35.21	117.18	8	4	15
Ent, T2P1	21	25.4532	2.2308	3.164	33.26	66.28	98.16	12	8	29
Ent, T2P2	21	17.1204	3.01	1.54	21.2	65.41	98.16	4	0	13
Ent, T2P3	21	13.2748	1.8036	3.404	14.79	63.82	98.16	8	4	15
Ent, T2P4	21	10.8208	1.336	1.372	14.1	66.45	98.16	8	4	17
Ent, T2P5	21	11.2972	2.9588	3.552	14.2	51.86	98.16	8	4	16
GGR, T2P1	22	16.036	1.3596	6.868	19.14	56.25	110.06	12	8	21
GGR, T2P2	22	9.3984	2.5996	4.388	13.32	56.7	110.06	8	4	18
GGR, T2P3	22	18.9624	2.2464	4.464	23.23	56.47	110.06	12	8	24
GGR, T2P4	22	11.6136	3.2184	19.328	18.95	19.2	110.06	12	8	27
GGR, T2P5	22	8.9156	0.4832	3.192	11.33	26.03	110.06	8	4	15