FUEL MOISTURE AND DEVELOPMENT OF IGNITION AND FIRE SPREAD THRESHOLDS IN GORSE (*Ulex europaeus)*

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Abstract

Shrub fuels are capable of extreme fire behaviour under conditions that are often moderate in other fuels. There is also a narrow range of conditions that determine fire success in these fuels, below which fires may ignite but hardly spread and above which they ignite and develop into fast moving and high intensity fires. This is due to the elevated dead fine fuels that dry rapidly and carry fire. Fire danger rating systems designed for forest and grassland fuels do not predict fire potential in shrub fuels very well. Fire management requires fire danger rating systems to provide accurate and timely information on fire potential for all important fuel types.

Studies of fuel moisture, ignition and fire spread were carried out in the field in gorse (*Ulex europaeus L.*) shrub fuels to predict the moisture content of the elevated dead fuels and to define the conditions that govern fire development. The accuracy of the Fine Fuel Moisture Code (FFMC) of the Canadian Forest Fire Weather Index (FWI) System to predict moisture content of this layer was assessed. A bookkeeping method to predict moisture content was developed based on semi-physical models of equilibrium moisture content, fuel response time and the FFMC.

The FFMC predicted moisture content poorly, because the FWI System is based on the litter layer of a mature conifer forest. The gorse elevated dead fuel layer is more aerated and dries faster than this conifer forest litter layer. The bookkeeping method was reliable and allowed adjustment of fuel response time based on weather conditions. Difficulties in modelling meteorological conditions under the gorse canopy limited its accuracy. Separate thresholds determined ignition and fire spread success, with both based on the elevated dead fuel moisture content. Options to improve the shrub fire danger rating system were presented based on these findings.

The results are significant because they are based on data collected in the field under real conditions. Validation of these results and extension to other shrub fuels is required before the findings are used to change current models. However, the study has significantly advanced the knowledge of fire behaviour in shrub fuels and will contribute to safe and effective fire management in these fuels.

Chapter 1:
Introduction

1.1. Shrub vegetation

Shrublands, or heathlands[1], occupy one of the largest climatic ranges in the world and inhabit a wide range of conditions, from lowland to alpine climatic zones. They can be divided into two distinct groups – dry-heathland on well-drained soil, and wet-heathland on seasonally waterlogged soil. Shrubland communities are known by many different names, depending on where they occur, e.g. chaparral (California), mallee scrub (Australia), fynbos (South Africa), garrigue (France), maquis (Mediterranean area) and matorral (Chile) (Di Castri, 1981; Specht, 1979a). Common characteristics of all shrubland vegetation are (Specht, 1979a):

- communities are evergreen and sclerophyllous (adapted to survive long summer droughts);
- the presence of the heath families – Diapensiaceae, Empetraceae, Epacridaceae, Ericaceae, Grubbiaceae, Prionotaceae, Vaccinaceae;
- shrublands are often found on the most infertile soils, and this low soil nutrient status appears to control their distribution.

Shrubland vegetation is usually susceptible to fire during periods of water stress, and fire is an important process in many shrubland ecosystems. Sclerophylly is one of the important and remarkable adaptations that allows this vegetation to persist in harsh environments, and is characterised by the presence of small evergreen leaves with thick cuticles to minimise water loss. Specht (1979a) suggests subdivision and characterisation of shrubland vegetation based on the height of the uppermost stratum (Table 1.1).

[1] In fire management circles, these terms are often used loosely and interchangeably, with the strict convention in Table 1.1 often not adhered to. For simplicity's sake, in this thesis shrub or shrubland refers to all heathland vegetation and fuel complexes.

Table 1.1. Definition of shrubland vegetation according to the height of the uppermost stratum (Specht, 1979a).

Height of uppermost stratum	*Subdivision*
Shrubs >2m	Scrub
Shrubs 1-2m	Tall heathland
Shrubs 0.25-1m	Heathland
Shrubs <0.25m	Dwarf heathland

It is generally accepted that shrubland vegetation communities of the world originated in the southern part of the super continent of Gondwana. Once Gondwana broke up and the continents drifted apart, evolution of these communities continued into current forms and distributions. A comprehensive discussion of the origins and distribution of shrubland is contained in Specht (1979a).

1.2. Fire characteristics of shrub fuels

Fire is often important in shrubland ecosystems. Many shrub species have developed adaptations to survive and even flourish following fire, such as lignotubers, epicormic sprouting, prolific flowering, and seeds that remain viable in the soil for many years (Bond & Van Wilgen, 1996; Gill, 1981; Keith *et al.*, 2002; Naveh, 1994; Specht, 1979a, 1979b, 1981). Many shrub communities around the world are renowned for their flammability and ability to burn at very high rates of spread and extreme fire intensities. These occur under levels of fire danger which would not be considered extreme for other fuel types, such as forest and grass (e.g., Anderson & Pearce, 2002; De Luis *et al.*, 2004; Fernandes, 1998; Fogarty, 1996). Special characteristics that contribute to this phenomenon are:

- the presence of volatiles and other chemical compounds in foliage that contribute to the flammability of live foliage (Keith *et al.*, 2002; Specht, 1979a; Vines, 1981);
- a typically high elevated dead fine fuel load and low fuel bulk density, i.e., the elevated dead fine fuels are well-aerated, exposed to solar radiation in the absence of shading from tree canopies, and dry at faster rates than forest litter fuels (Catchpole *et al.*, 1998; Keith *et al.*, 2002);

- live fuels that can be an important fuel component with respect to fire behaviour (e.g., Davies & Legg, 2008; Davies *et al.*, 2006; McCaw, 1997; Weise *et al.*, 2005). This is in contrast to forest and grass fuels, where live foliage often has a damping or fire-inhibiting effect, apart from contributing to crown fires in forests (Cruz *et al.*, 2002; Van Wagner, 1974).

1.3. New Zealand shrub vegetation

The three major plant formations in New Zealand are forest, grassland and shrubland (often referred to as 'scrub'). Pure shrub communities cover approximately 4% of the land area of New Zealand, while a further 24% consists of shrub-grassland or shrub-forest mixtures (Newsome, 1987). Low fertility soils are common in New Zealand, and so shrub vegetation is widespread. The Ericaceae family is very limited in New Zealand, and there is generally a complex pattern of shrubland communities across the country. However, manuka (*Leptospermum scoparium*) and kanuka (*Kunzea ericoides*) are common and widespread throughout the country. Other important species include matagouri (*Discaria tomatou*), *Dracophyllum*, *Hebe*, *Coprosma* and *Pteridium* species (Burrows *et al.*, 1979; Newsome, 1987).

Fire has played a major role in shaping the landscape in New Zealand, with extensive burning since the arrival of humans approximately 1000 years ago resulting in approximately 70% of the area of the country being cleared of forests. Much of the forest area that was burned was replaced by shrublands and tussock grasslands (McGlone, 1983; Ogden *et al.*, 1998). However, fire has not been the major driver in all cases – some shrublands originated from natural soil processes independently of natural- or human-caused fire (Burrows *et al.*, 1979). Fire occurrence in New Zealand prior to human settlement was mostly infrequent and patchy (Ogden *et al.*, 1998; Rogers *et al.*, 2007). In addition, most New Zealand flora do not display fire adapted traits, with the possible exception of manuka which has shown evidence of serotiny (Bond *et al.*, 2004). Many introduced plants have successfully invaded New Zealand, including shrubs such as gorse (*Ulex europaeus*), *Hakea* species, broom (Cytisus scoparius), heather (*Calluna vulgaris*), *Juncus* species and Spanish heath (*Erica lusitanica*) (Burrows *et al.*, 1979; Newsome, 1987).

1.3.1 Gorse

Gorse *(Ulex europaeus*) is an evergreen, leguminous (member of the Fabaceae family) shrub with simple, spiny leaves. The genus comprises around 20 species, and *U.europaeus* is the most common and widespread. It is prickly, with sharp spines growing in the axils of leaves (Hoshovsky, 1989; Zabkiewicz, 1975). It flowers prolifically and often throughout the year, with peaks in spring/early summer and autumn (Kennedy & Hydewyat, 1969; Zabkiewicz, 1975). Gorse is a highly successful and fast-growing shrub species with a lifespan of approximately 30 years and it often occupies degraded or disturbed land. It has nitrogen-fixing bacteria in nodules on the roots, is able to sprout from the stem and even from roots if cut or burned to ground level, and produces vast amounts of seed that can remain viable for over 30 years in the soil (Kennedy & Hydewyat, 1969; Prasad, 2003; Tarayre *et al.*, 2007; Zabkiewicz, 1975).

Gorse can represent a significant fire hazard (Alexander *et al.*, 2007), with large amounts of dead elevated fine fuels (particles with diameter less than 5 mm) suspended from branches within the canopy layer and large amounts of dead litter on the ground. Total fuel loads of 46-52 t ha^{-1} have been reported for *U.europaeus* shrublands in Spain, representing a combination of elevated and litter fuels (Vega *et al.*, 2005). Sampling in New Zealand found total fuel loads of 26-74 t ha^{-1} across a range of 58 sites with significant variability in fuel age, cover and climate zones. Elevated dead fine fuel loads represented on average 33% of the total available fuel load for each sample (Scion, unpubl. data). Studies of post-fire recovery in gorse and other shrub stands around Wellington found that dry matter accumulated at a rate of 10-15 t ha^{-1} per annum in stands up to 10 years old (Egunjobi, 1969). In the Mediterranean areas of Spain, stands dominated by *U.parviflorus* had biomass loads of 30-40 t ha^{-1}, with high horizontal and vertical continuity. In these areas the proportion of dead fine fuel was found to represent approximately 50% of the total biomass (De Luis *et al.*, 2004). Stands of gorse are often even-aged and establish in disturbed areas at the same time, such as following land clearing or fire (Hill *et al.*, 2000).

The natural distribution of gorse is predominantly across central and western Europe. However, given its hardiness and ease of establishment, it has spread and become a serious weed problem in a number of countries and regions, such as Hawaii, Australia, Chile, Costa Rica, New Zealand and the Atlantic coastal areas of North America (Hoshovsky, 1989; Tarayre *et al.*, 2007; Zabkiewicz, 1975). Gorse was introduced to New Zealand in the 19th century from Britain in order to provide shelter and hedgerows for livestock. It subsequently spread rapidly across large areas of the country to become a weed problem (Isern, 2007; Rees & Hill, 2001). The land area of New Zealand occupied by gorse at different levels of dominance, from 'pure' stands to pasture and gorse mixes, has been estimated at approximately 700,000 ha (Blaschke *et al.*, 1981) – nearly 3% of the land area of the country. It commonly grows to heights of 2-4 m, although this is dependant upon locality (Hill *et al.*, 2000). Given its widespread distribution and flammable nature, it accounts for a significant proportion of the wildfires in shrub fuels in New Zealand, as described in the following section.

1.4. Shrub fires in New Zealand

A recent analysis of 16 years of fire records in New Zealand (from 1991-2006) found that fires in shrub fuels accounted for an average of 40% of the total annual area burned nationally, or 2330 ha per year. Over this 16-year period, the largest proportion of the shrub area burned occurred was in Otago, followed by Northland, Canterbury, West Coast and Southland. The South Island accounted for 60% of the total shrub area burned, and over a third of the remaining 40% in the North Island was recorded in Northland. Wildfires escaping from land-clearing burning (burn-offs) accounted for 42% of the total shrub area burned over this period. Miscellaneous and unknown causes accounted for a further 30% of the shrub area burned, with other significant causes being vehicles, railways, incendiary (fireworks and explosives), power lines and recreation (Anderson *et al.*, 2008; Doherty *et al.*, 2008).

The study referred to above did not define gorse fuels separately from other shrub fuels. The shrub fuel type contained a number of species mixes including gorse, manuka/kanuka, broom, wetlands (pakihi) and native hardwood shrubs (matagouri, Dracophyllum species, broadleaf, etc.). However, given the flammable nature and widespread distribution of gorse, fire managers recognise that gorse represents a significant proportion of the ‘fire problem’ in New Zealand.

1.5. Thesis objectives and structure

The three research objectives of the work described here were:

1. To understand and model fuel moisture within the elevated dead fine fuel layer of gorse.
2. To define threshold conditions for successful fire development (both ignition and fire spread) in gorse.
3. To explore improved methods for fire danger rating in New Zealand shrub fuels.

Five fuel strata are referred to in this thesis: live, elevated, near-surface, surface and duff fuels. Live fuels represent green foliage < 3 mm diameter that are generally found in the canopy layer. Elevated dead fuels are dead leaves, needles and small twigs < 5 mm diameter located from 50 cm above ground level to the top of the fuel canopy (and separated from the near-surface fuels). Near-surface fuels are a layer of suspended leaf/needle, twig and bark material from the overstorey < 5 mm diameter, located immediately above the surface layer and up to approximately 30 cm above the ground in shrub fuels (up to 1 m in forests) (Gould, McCaw, Cheney, Ellis, Knight *et al.*, 2007; Gould, McCaw, Cheney, Ellis, & Matthews, 2007). Surface fuels are the top 10 mm of the litter layer, including dead leaves, needles and small twigs <5 mm diameter. Duff is the loosely compacted and decomposing organic layer immediately below the surface layer and above the mineral soil layer.

The fuel moisture modelling component (objective 1) focussed on the elevated dead fuel layer only. This layer was observed in previous field experiments and in this study, as well as from operational experience, to be the primary fuel layer governing fire development and spread. Fires were seen to ignite and spread in this fuel layer independently of the surface (litter) or near-surface fuel layers. The focus was therefore to develop a model to accurately predict fuel moisture in the elevated dead fuel layer.

The second research objective was to define the threshold conditions that govern both ignition and fire spread success in the elevated dead fuel layer. Operational experience and observations from research experiments in the field showed that ignition success did not necessarily mean that fires would develop and spread. Fuels would sometimes ignite and burn out a gorse clump without spreading into adjacent fuels, and in some cases fuels were very close to the burning clump without the fire spreading. Fire managers need to understand these different conditions of fire potential. Fire preparedness and response requirements in conditions where fuels ignite but fires do not develop and spread will differ considerably from those where ignitions result in spreading fires that require prompt suppression and containment.

The third research objective explored options to improve the system for rating fire danger in New Zealand shrub fuels by incorporating the results from the fuel moisture and fire threshold modelling work in the first two objectives. The current model to assess fire danger levels in shrub fuels in New Zealand uses the Fine Fuel Moisture Code (FFMC) of the Fire Weather Index System and wind speed as inputs. A key assumption of this model is that fire danger is always considered to be low at FFMC values below 60. This FFMC value is intended to represent the ignition threshold for shrub fuels, but is based on limited data and requires validation.

A summary of the thesis structure is provided below:

- Chapter 2 reviews the current knowledge and practices in relation to fire in shrub fuels. This includes fuel moisture prediction, fire behaviour modelling and fire danger rating. The fire danger rating section provides an overview of the principles of fire danger rating systems and the major fire danger rating systems in use around the world, before summarising progress towards developing fire danger rating systems applicable to shrub fuels.

- Chapter 3 describes the two study sites used to collect the field data for the work presented in this thesis.

- Chapter 4 presents results from attempts to model the meteorological conditions under the canopy (at fuel level) from weather observations at a weather station in the open following standard fire weather reporting procedures. The current fire weather and fire danger monitoring system uses standard weather station observations as inputs (and not those at the fuel level under the canopy).

- Chapter 5 explores approaches to predict the moisture content of the elevated dead fuel under the gorse canopy. The reliability of the Fine Fuel Moisture Code of the Fire Weather Index System is evaluated, and alternative modelling approaches examined. This chapter is a manuscript that has been accepted for publication by the Canadian Journal of Forest Research. It has been inserted into the thesis largely as submitted to the journal, with the exception of some minor changes and additions where necessary. Some repetition of background information (as provided in Chapters 1 and 2) is therefore evident.

- Chapter 6 defines thresholds for ignition and fire spread in gorse fuels, based on results of fire experiments in the field. This chapter is a manuscript that has been resubmitted to the International Journal of Wildland Fire following peer review. Repetition of background information will therefore again be evident.

- Chapter 7 describes attempts to improve the system of fire danger rating for shrub fuels in New Zealand. This includes attempts to revise the current system by incorporating findings from Chapters 5 and 6. Alternative approaches to fire danger rating in shrub fuels are also discussed.

- Chapter 8 provides general discussion and conclusions from the results presented in the previous chapters (4-7). The purpose of this chapter is to integrate and summarise these key findings and, in particular, to discuss the implications and considerations for any possible operational application or implementation of these results. A list of recommendations for further research as well as management/operational considerations is provided.

1.6. Statistical methods

Assessment of model goodness-of-fit was carried out by comparing predicted values from the models against actual values from the corresponding field data. In these cases, goodness-of-fit was reported by the values of the coefficient of determination (R^2), mean error (ME) and root mean square error (RMSE). The R^2-value was based on the regression of observed on predicted values, and provided a measure of model precision (the proportion of the variation in the observed values explained by the predicted (model) values). The ME was simply the average of the differences between observed and predicted values, and provided an indication of bias in the model. The RMSE combined the measures of precision (R^2) and bias (ME), and was therefore used as the most reliable indicator of the most appropriate model. Plots include a solid line that represents the line of perfect agreement between observed and predicted, and a dashed line that represents the regression of observed versus predicted values.

Other specific statistical procedures are described within the relevant chapters where appropriate, such as the autoregressive procedures for time-series data (Chapters 4 and 5) and the logistic regression analyses and model selection processes for determining ignition and fire spread thresholds (Chapter 6).

Chapter 2:
Review of fire behaviour and fire danger rating in shrub fuels

2.1. Introduction

This chapter presents an overview of research related to fire behaviour and fire danger rating in shrub fuels. This includes shrub fuel characteristics, fuel moisture prediction, fire behaviour modelling and fire danger rating. The discussion on fire danger rating provides an overview of the principles and history of fire danger rating, and then describes the main fire danger rating systems in use around the world. This is followed by a summary of the approaches to develop fire danger rating systems for shrub fuels. The focus of this review chapter has not been limited to gorse but includes all shrub fuels, since there was limited work that focussed exclusively on gorse fuels.

2.2. Fuel characteristics

Physical fuel characteristics influence the likelihood of ignition, fire behaviour and fire spread in different fuel types (Papio & Trabaud, 1990). Characteristics such as fuel particle size and shape, fuel load or quantity, fuel distribution and proportion of dead and live fuels, have a strong influence on fire behaviour (Chandler *et al.*, 1983; Marsden-Smedley & Catchpole, 1995a; Pyne *et al.*, 1996). Shrub fuels are generally characterised by high fuel loads consisting of elevated fine dead material and low bulk density (Catchpole *et al.*, 1998; Keith *et al.*, 2002), the presence of volatile compounds in the foliage (De Lillis *et al.*, 2009; Keith *et al.*, 2002; Specht, 1979a; Vines, 1981) and the fact that live foliage can be an important contributor to flammability (Davies & Legg, 2008; Davies *et al.*, 2006; McCaw, 1997; Weise *et al.*, 2005). Fuel continuity and distribution varies between different types of shrublands, but gorse fuels often form dense and continuous even-aged stands (Hill *et al.*, 2000).

Fuel characteristics and fire behaviour have been described for a range of shrubland fuels in the United States. Physical characteristics of five common shrub fuels in Northern California were described by Countryman (1982), including ash content, fuel density, extractive content, surface-to-volume ratios, heating values, dead and live fuel loads, and vertical arrangement. Paysen and Cohen (1990) found that, contrary to common belief, the amount of dead fuel in chamise chaparral (*Adenostoma fasciculatum*) shrub was not related to canopy age. Other factors, such as climatic variability, insects and diseases were suggested as the main determinants of the amount of dead fuel in these shrub complexes. Countryman and Dean (1979) found that 55% to 75% of the total standing fuel in chaparral was living material. Many shrub species found on the North Carolina coastline had branches arranged in a pattern that enhanced their flammability. The branches supported a dense mass of fine fuel particles above the litter surface (Blackmarr & Flanner, 1975). This arrangement of branches was also evident in Californian chaparral and had a significant effect on fire intensity during prescribed burns (Schwilk, 2003).

Fuel characteristics of Tasmanian buttongrass (*Gymnoschoenus sphaerocephalus*) moorlands were described as part of a broader study on fire behaviour. Models were developed from field data to predict both total and dead fuel loads, with total fuel load reliably predicted using fuel age and site productivity. Site quality was subjectively assessed as low or medium and based on the geology of the area. Fuel age was determined through counts of either nodes or growth rings. Improved predictions of total fuel load were obtained using shrub cover in addition to site quality and fuel age, but assessment of cover was highly subjective and was therefore excluded. The model to determine dead fuel load only was based on the total fuel load, and was largely independent of site productivity. Other fuel characteristics were also described, such as surface area to volume ratio, particle density, heat content and mineral and silica levels (Marsden-Smedley & Catchpole, 1995a; Marsden-Smedley *et al.*, 1999).

Fire behaviour studies in mallee shrublands of southwestern Australia found that total fuel loads remained relatively constant in vegetation older than 10 years, but the proportion contributed by the litter and dead fuels (of less than 6 mm diameter) continued to increase up to 20 years after fire. This explained the higher intensity fires observed in older stands compared to younger stands with similar fuel loads. Fuel height and cover was dominated by shrubs less than 1 m tall (McCaw, 1997).

In New Zealand, research into shrub fuel characteristics has focussed on developing models of available fuel load. Extensive destructive fuel sampling was carried out in a range of shrub fuel types across the country, with information collected on fuel load, cover and height (Fogarty & Pearce, 2000; Manning & Pearce, 2008). The fuel types sampled included both native (manuka/kanuka, wetlands) and exotic (gorse) shrublands. The most reliable models used fuel height to determine fuel load (Fogarty & Pearce, 2000).

Extensive work in a range of Mediterranean shrub fuels has been carried out to describe their physical characteristics. De Luis *et al.* (2004) found that mature Mediterranean gorse (*U.parviflorus*) shrublands in NW Spain had very high biomass (30-40 t ha^{-1}), with fine dead fuel accounting for approximately 50% of the total. Similar studies corroborated these findings (e.g., Baeza *et al.*, 2006). Fuel loads were also been found to accumulate rapidly, with twelve-year old *U.parviflorus* communities having fuel loads two to five times greater than those of three-year old communities (Baeza *et al.*, 2002). Sampling in *U.europaeus* shrublands in Spain found fuel loads to be 46-52 t ha^{-1}, representing a combination of elevated and litter fuels (Vega *et al.*, 2005). Attempts to develop models of fuel load have reported contrasting results, with Pereira *et al.* (1995) finding that neither plant volume nor basal stem diameter were suitable to determine fuel load in *U.parviflorus* shrublands. However, Baeza *et al.* (2006) found basal diameter to be the most reliable predictor of biomass in similar shrublands in Spain.

Papio and Trabaud (1990) assigned Mediterranean shrub fuels into three categories of species according to their fire hazard, using the surface area-to-volume ratio and the specific gravity of the fuel particles as the basis for categorisation. They also studied the aerial canopy components of five shrub species (Papio & Trabaud, 1991), describing canopy fuel size distribution, fuel load by size class, porosity, dead-to-live fuel ratio, and the vertical fuel distribution. The five species were then grouped into three classes from lowest to highest flammability depending on their fuel load, porosity and characteristics of the dead fuel components (Papio & Trabaud, 1991).

Dimitrakopoulos (2002) developed seven fuel models for Mediterranean vegetation types in Greece for input into the US BEHAVE fire prediction system (Andrews *et al.*, 2005). The fuel models were based on physical characteristics of the fuels: fuel loads of different size classes, litter load and depth, total fuel load, and average height and cover of shrub layers.

In South Africa, fynbos shrub fuels were described in terms of structure, fuel chemistry and moisture content. The physical characteristics (fuel continuity, chemical composition) of fynbos vegetation make it favourable to fire. Fynbos was judged to be more flammable than Chilean mattorral, but less flammable than Californian chaparral or Australian eucalyptus woodlands as a result of lower crude fat contents and higher foliar moisture contents (Van Wilgen *et al.*, 1990).

2.3. Fuel moisture

Fuel moisture influences all aspects of fire behaviour, including ease of ignition, availability of fuel for combustion, and the rate of combustion of each fuel class (based on size and live or dead condition) (Brown & Davis, 1973; Chandler *et al.*, 1983; Pyne *et al.*, 1996). Fuel moisture is therefore a central component of fire danger rating systems and fire behaviour models, and its accurate calculation is essential. Shrub fuels are characterised by high elevated dead fine fuel loads that are well-aerated and have faster drying rates than surface fuels (Catchpole *et al.*, 1998; Keith *et al.*, 2002). Live fuels can also be important contributors to fire behaviour (e.g., Davies & Legg, 2008; Davies *et al.*, 2006; McCaw, 1997; Weise *et al.*, 2005). Most fuel moisture models have been developed to determine the moisture content of fine fuels in surface litter layers or grasses and low shrubs, not for the elevated dead fine fuels (Marsden-Smedley & Catchpole, 2001).

2.3.1. Dead fuel moisture

Several studies in Australian shrublands have investigated fuel moisture relationships and prediction of dead fuel moisture content (Marsden-Smedley & Catchpole, 2001; McCaw, 1997; Pippen, 2007). An empirical model was developed to predict dead fuel moisture content in Tasmanian buttongrass moorlands using relative humidity and dew point temperature. The fuel moisture model in the McArthur grassland model was also found to be reliable for these fuels (Marsden-Smedley & Catchpole, 2001). McCaw (1997) found that dead fuels in mallee shrub in Western Australia dried faster than eucalypt forest litter fuels following rain. An equilibrium moisture content (EMC) model based on Nelson (1991) that used inputs from meteorological observations was the most accurate model to predict fuel moisture in mallee shrub. Pippen (2007) carried out extensive laboratory studies to determine EMC values for shrub fuels from the Sydney Basin area. He evaluated a range of existing fuel moisture models (mostly from Australia) to predict fine dead fuel moisture in these shrub fuels. None of these models predicted shrub fuel moisture well. The bookkeeping model of Catchpole *et al.* (2001) that incorporates the EMC function of Nelson (1984)[2] yielded the most accurate predictions. A process-based model that incorporates the physical processes of moisture transfer (Matthews, 2006) performed almost as well as the Catchpole *et al.* (2001) model at fuel moisture contents less than 25%. However, further work was recommended to validate and improve this model for shrub fuels and address known issues at high moisture levels.

In New Zealand, the Fine Fuel Moisture Code (FFMC) of the Fire Weather Index (FWI) System (refer Section 2.5.3.4) is used to predict fuel moisture in all fuel types. Limited work to explore the relationship between the dead fuel moisture content in gorse shrub fuels and the FFMC showed that the FFMC was not suitable to determine dead fuel moisture content in these fuels (Ellis, 1994; Fagan, 1999). This is not surprising, since the FFMC is empirically-derived from the litter layer of mature conifer forest in Canada. The elevated dead and litter fuel layers in shrub fuels are very different to this reference fuel type (Alexander, 2008; Anderson, 2009).

2.3.2. Live fuel moisture

The role of live fuel moisture in fire behaviour is generally regarded to be one of inhibiting fire spread, acting as a ‘heat sink’ (Burgan, 1979; Tunstall, 1988). However, in shrub fuels it is known that live fuel moisture can contribute to ignition and fire spread. Whilst moisture content in dead fuels is controlled by environmental factors (relative humidity, rainfall and temperature), the moisture content of live fuels

[2] A detailed explanation of this model is provided in Chapter 5.

is mainly controlled by physiological processes (Chandler *et al.*, 1983; Deeming *et al.*, 1977; Tunstall, 1988). However, environmental conditions do also affect live fuel moisture, particularly seasonal drought (Burgan, 1979). Chandler *et al.* (1983) state that fires will burn at high intensity when live fuel moisture falls below 75%.

Distinct seasonal trends in live fuel moisture have been found in many shrub fuels in the USA, with an increase in the spring followed by a gradual decrease as the growing season progresses (Countryman & Dean, 1979; Weise *et al.*, 1998). A study of Pocosin shrubs in North Carolina showed that evergreen shrubs usually had a lower live fuel moisture content than deciduous shrubs at all times of year (Blackmarr & Flanner, 1975). Live fuel moisture content in Californian chaparral has a significant effect on fire behaviour. Countryman and Dean (1979) suggested that the seasonal pattern of live fuel moisture content was related to physiological activity, which was in turn influenced by soil moisture and soil and air temperature. Site quality also influenced moisture content, with good sites resulting in more new growth and higher moisture contents than on poor sites. In Alaska, Norum and Miller (1984) found that the moisture content of live shrub and herbaceous plants was little affected by weather, but was largely dependent upon species physiology and time of year. Levels of moisture content followed the same general pattern over the season, regardless of weather conditions.

Burgan (1979) developed a theoretical model to estimate live fuel moisture content for the US National Fire Danger Rating System (NFDRS). Certain fuel types in the NFDRS have both live and dead components. This model determines the moisture content of the live components using weather observations (daily maximum and minimum relative humidity and temperature, and precipitation duration) and drying rates derived from the climatic zone. The amount of herbaceous vegetation is transferred between live and dead fuel categories as a function of the live fuel moisture content. Fuel models used in the USA for fire behaviour prediction were recently updated and expanded, but retained this live fuel moisture model and fuel load transfer approach (Scott & Burgan, 2005). However, a recent study using grassland curing[3] data showed that fuel moisture cannot be used to indicate the amount of dead material in grasslands (Andrews *et al.*, 2006).

McCaw (1997) found little seasonal variation in live fuel moisture contents of mallee shrub in Western Australia. Moisture contents were similar to those in shrub fuels from Mediterranean environments of the United States and southern Europe, although seasonal variation was considerably less in mallee. Fuel moisture values were slightly lower than those recorded in South African fynbos. However, samples were collected for only one year, and more data were required to fully investigate this apparent lack of seasonal variation in mallee.

Pippen (2007) sampled live fuel moisture at fortnightly intervals for two years from four shrub and one sedge species in the Sydney Basin of eastern Australia. Seasonal and phenological variation was evident for the shrub species. The sedge species exhibited no distinct phenological stages and little seasonal variation in live fuel moisture content. A simple regression model was developed to predict live fuel moisture content for the shrub species, based on the average dew point temperature over the preceding seven-day period. However, this model would have limited applicability beyond the study area or the range of data from which it was developed.

A model developed to predict live fuel moisture of shrubs in Catalonia (Spain) used soil water availability and the Buildup Index (BUI) of the Canadian Forest Fire Weather Index (FWI) System (Castro *et al.*, 2003). However, this approach was limited in that these models did not account for physiological processes that influence moisture content. Long-term data also showed clear evidence of seasonal variation in live fuel moisture content in these fuels (Castro *et al.*, 2006). Studies in Spanish *Rosmarinus officinalis* shrub modelled live fine fuel moisture using soil moisture and the accumulated minimum daily temperature from the previous seven days. However, other factors such as site quality, microclimate, soil type, fuel age and solar radiation also influenced the live fuel moisture content (Tudela *et al.*, 2002). The Keetch-Byram drought index (Keetch & Byram, 1968) accurately modelled the live moisture content of understory shrubs in Greece. However, it did not adequately reflect the

[3] Grassland curing refers to the proportion of dead material in a grassland fuel complex (Cheney & Sullivan, 1997).

moisture status of pine needle litter, nor the soil water content of the upper litter layers (Dimitrakopoulos & Bemmerzouk, 2003). Viegas *et al.* (2001) found that the Drought Code (DC) of the FWI System estimated the live fuel moisture content of Portuguese shrub fuels well during the summer, but the correlation was species- and site-dependent. However, in heather (*Calluna vulgaris*) moorlands of Scotland the three moisture codes of the FWI System all poorly predicted live fuel moisture content. Development of a physiological model that captures seasonal changes in leaf conductance and water uptake was proposed for these fuels (Davies & Legg, 2008).

Remote sensing applications have also been studied to determine both live and dead fuel moisture content of shrub fuels. Bowyer and Danson (2004) reported that use of spectral reflectance to determine canopy water content yielded greater accuracy in grasslands than in forests or shrublands. This was largely because of greater spatial and temporal variability in environmental factors in these fuel types, compared to more uniform and continuous grasslands. However, Verbesselt *et al.* (2006) found promising relationships between indices derived from SPOT VEGETATION satellite imagery and moisture content in both grasslands and shrublands. Ustin *et al.* (1998) used remotely-sensed Airborne Visible Infrared Imaging Spectrometer data to estimate the water content of canopy fuels in Californian chaparral. Results indicated that it was possible to estimate canopy water content at a 20 m resolution. A combination of a water balance index and satellite-derived equivalent water thickness (EWT) measure was also suggested to monitor live fuel moisture in Californian shrublands (Dennison *et al.*, 2003). In Spanish shrub fuels, live fuel moisture was derived from foliage reflectance measured with a hand-held spectroradiometer. Initial results yielded reasonable estimates of fuel moisture (Piñol *et al.*, 1998). A similar study found that near-infrared reflectance spectroscopy predicted live fuel moisture content well (Gillon *et al.*, 2004). Chuvieco *et al.* (2004) developed a reliable empirical model for fuel moisture content of Mediterranean grasslands and shrublands. Model inputs were vegetation type, day of the year, and two satellite-derived inputs (the Normalised Difference Vegetation Index and Surface Temperature). With constant improvements in remote sensing technology, the use of remote sensing as a cost-effective and accurate method to determine live fuel moisture content for operational purposes could be possible in the near future.

2.4. *Fire behaviour*

Fires in shrub fuels often spread rapidly at very high intensities that challenge fire suppression efforts (Catchpole *et al.*, 1998). This can occur under conditions that would not normally be conducive to extreme fire behaviour in forest and grassland fuels (e.g., De Luis *et al.*, 2004; Fernandes, 1998; Fogarty, 1996; Keith *et al.*, 2002; Marsden-Smedley & Catchpole, 1995b). Fires in shrub fuels can also spread in the elevated fuel layers, independent of the surface or litter layers. This phenomenon has been observed in gorse fires in New Zealand (Scion, unpubl. data), Tasmanian buttongrass moorlands (Marsden-Smedley & Catchpole, 1995b) and other Australian shrublands dominated by dense stands of *Leptospermum* species (Cheney, 1981).

Field observations of fire spread in Tasmanian buttongrass moorlands were compared against predictions of rate of spread from seven published fire behaviour models. These models included forest, grassland and shrubland fuel types. None of them predicted rate of spread reliably, with the Australian McArthur Forest and Grassland Fire Danger Meters performing particularly poorly. An empirical fire behaviour model was developed for buttongrass moorlands to predict rate of spread using wind speed, fuel age and dead fuel moisture content (Marsden-Smedley & Catchpole, 1995b).

Fire behaviour studies in mallee shrublands of southwestern Australia again found that existing models predicted rate of fire spread poorly in these fuels (McCaw, 1997). Rates of spread in mallee fuel types were consistently higher than those predicted for other fuel types, in many cases at least twice that for other shrub fuel types. The exception was South African fynbos shrub fuels, which tended to exhibit faster rates of spread under similar conditions (McCaw, 1997; McCaw *et al.*, 1995). This contrasts slightly with previous work, which has indicated fynbos to be less flammable than Australian eucalyptus woodlands (Van Wilgen *et al.*, 1990).

Data from 29 experimental burns and 3 wildfires were used to develop a fire behaviour model for New Zealand shrub fuels. The model uses the Initial Spread Index (ISI) component of the Fire Weather Index (FWI) System to predict rate of spread. Gorse and native shrub species (manuka, kanuka and wetlands) are currently grouped together for the model. The dataset used to develop the rate of spread model also lacks observations from fire spread at moderate to high wind speeds and ISI values (Anderson, 2009). A complete description of this model is contained in Chapter 7 (section 7.1).

Collaborative Australasian efforts to develop fire spread models for shrubland fuels (Catchpole *et al.*, 1998) found that wind speed accounted for the major variation in spread rate in New Zealand manuka/kanuka fuels. Moisture content was not significant (neither elevated dead nor litter fuels). Models were also developed using combined New Zealand and Australian data. The best model used fuel height and wind speed to predict rate of spread. This model was reliable for wildfire data from eastern Australia and New Zealand, but was less accurate for data from fires in Western Australian mallee shrub and Tasmanian buttongrass moorlands. This was possibly due to the lack of response to moisture in the model, particularly in the case of the mallee fuels (Catchpole *et al.*, 1998).

Rothermel's fire spread model (Rothermel, 1972) forms the core of the United States National Fire Danger Rating System and the Fire Behavior Prediction System. However, the model assumes continuous and homogeneous fuels, which is not always the case at a landscape scale. Big sagebrush (*Artemisia tridentata* ssp. *wyomingensis* and *A.tridentata* ssp. *vaseyana*) is a fuel type in the western US that forms a discontinuous and patchy pattern, violating the assumptions of Rothermel's fire spread model. Research to improve fire behaviour prediction in this fuel type found that the amount of cured vegetation, height and cover of sagebrush and quantity of other vegetation such as grasses and forbs strongly influenced fire behaviour (Brown, 1982).

Observed fire behaviour from 14 experimental fires in South African fynbos was compared with predictions using Rothermel's fire spread model. Rothermel's model underpredicted rate of spread, flame length and intensity. Predictions were improved by changing the estimate of fuel bed depth. Fire behaviour in other shrubland fuels was also compared against that in fynbos. Rates of spread in fynbos were found to be higher than in most other fuels. This most likely corresponded to differences in fuel characteristics, e.g. fuel bed depth, bulk density, and presence or absence of understory fuels (Van Wilgen *et al.*, 1985). Catchpole and Catchpole (1991) modified the moisture damping (interference of fuel moisture with combustion processes) component of Rothermel's rate of spread model and fitted this revised model to data from fynbos experimental burns. The revised model predicted rate of spread better than Rothermel's original model.

Fire spread prediction in Europe has been largely based on Rothermel's model (Fernandes, 2001). Significant inaccuracies were found when Rothermel's model was used to predict fire spread in Portuguese shrub fuels. Attempts to use the Initial Spread Index of the Fire Weather Index System to predict shrub fire rate of spread indicated that further investigation of the relationship between the Fine Fuel Moisture Code (FFMC) and actual dead fuel moisture was required (Fernandes, 1998). An alternative empirical approach to predict rate of spread in shrub fuels was developed, with rate of spread accurately predicted using wind speed, aerial dead fuel moisture content, and vegetation height. Further investigation of the effect of slope on fire spread and dead fine fuel moisture relationships was recommended (Fernandes, 2001). Dimitrakopolous and Dritsa (2003) developed nomographs[4] to predict rate of spread, intensity and flame length for Mediterranean shrub fuels using the US BEHAVE fire behaviour prediction system (Burgan & Rothermel, 1984). The BEHAVE system uses the Rothermel fire spread model. Predictions generally matched fire behaviour observations. Xanthopolous (2002) developed unique fuel models using the BEHAVE system, based on estimates of shrub biomass from regression equations.

In maquis fuels in Turkey, Bilgili and Saglam (2003) found that rate of spread was closely related to wind speed, total fuel load and mean height. Fuel moisture was not significant, possibly due to the narrow range of fuel moisture contents under which experimental burning was conducted. Fuel moisture content was also not significant to predict spread rate in shrub fuels of northeastern Portugal using data from small micro-plots. An empirical model using wind speed and fuel height predicted fire spread well (Fernandes *et al.*, 2000). Fire experiments in Spanish shrublands,

[4] Nomographs are "sets of graphs (computational charts) designed and organised for the graphic solution of complex mathematical equations without calculations" (French & Vierck, 1970 in Dimitrakopolous & Dritsa, 2003).

including gorse, found that moisture content was also not significant. An empirical fire spread model was developed using wind speed and fuel height (Vega *et al.*, 1998). However, another study in Mediterranean gorse (*U.parviflorus*) in Spain found fire behaviour to be highly dependent on fuel moisture content. Moisture contents were markedly lower in older stands of gorse than in younger stands, due to accumulation of large amounts of dead fuels in the older stands and a possible decrease of water content in the live phyllodes with fuel age. Fire rate of spread, fuel load and fire intensity all increased with fuel age and this accounted for the ability of mature stands to support high-intensity fires under moderate weather conditions (Baeza *et al.*, 2002).

Fire behaviour studies in gorse and heather in the United Kingdom combined empirical and theoretical approaches to develop a rate of spread model using fuel bulk density and wind speed (Thomas, 1970, 1971). The effect of fuel moisture on rate of spread was incorporated in the model, since the bulk density measurements included the water content of the fuels. Hobbs and Gimingham (1984) characterised fires and post-fire response in Scottish heathlands dominated by heather (*Calluna vulgaris*) in terms of temperature, rate of spread and fire intensity. They developed a regression equation that related maximum temperature to vegetation height, fire width and wind speed. More recent work in heather moorlands in Scotland found canopy height and wind speed to be the most important variables affecting fire spread rate, with moisture content not significant. However, there was inadequate distinction between live and dead fuel moisture components, due to the difficulties in separating these components in this fuel type (Davies *et al.*, 2006).

Uncertainty around the significance of moisture content is a problem in developing rate of spread models for shrub fuels, as evidenced by contrasting results from various modelling efforts reviewed here. This may be due to insufficient variability in moisture data in some field experiments. However, it is clear that further investigation of the role of moisture content in determining spread rate in shrub fuels is required (Catchpole, 1999; Catchpole *et al.*, 1998).

2.3.1. Ignition and fire spread thresholds

Shrub fuels have a very narrow and well-defined threshold, below which fuels may ignite but do not spread (i.e., burn individual bushes or clumps), and above which ignitions rapidly develop into fast-spreading and very high-intensity fires. This has been described as an 'on/off switch in terms of no ignition/no fire spread versus an extreme type rate of fire spread and intensity' (Alexander, 2008). It is critical to determine conditions in these shrub fuels under which ignition sources are likely to result in wildfires that spread and require suppression effort for effective fire management. This information is also required so that safe and effective prescriptions for controlled burning operations may be developed.

Information on ignition thresholds in surface fuels is limited (Plucinski & Anderson, 2008). Studies have been undertaken to determine ignition thresholds for a variety of fuel types through small-scale laboratory studies and field ignition trials. Laboratory studies have the advantage over field trials of providing controlled conditions and reduced costs and risks. However, field ignition trials allow the variability and complexity of 'real world' conditions to be incorporated into model development (Beverly & Wotton, 2007). Studies have focussed on ignition or fire spread thresholds in grass fuels (e.g., de Groot *et al.*, 2005; Manzello *et al.*, 2006; Stockstad, 1976) and the surface/litter layers in forests (e.g., Lawson *et al.*, 1994; Lin, 1999; Stockstad, 1975; Tanskanen *et al.*, 2005), including logging slash (Blackmarr, 1972). The Canadian Forest Fire Weather Index (FWI) System is in part based on extensive small-scale test fires conducted in the field in surface fuels across Canada between 1940 and 1961. Models that predict the probability of sustained flaming in forest and grass fuels were developed by Beverly and Wotton (2007) using this historic test fire dataset.

Some studies have been carried out to determine ignition thresholds in shrub fuels. Guijarro *et al.* (2002) did laboratory ignition tests and found that crushed *U.europaeus* litter had one of the highest ignition frequencies, rate of spread and combustion of the fuels tested. Plucinski and Anderson (2008) conducted laboratory studies of ignition thresholds in the litter layer of Australian shrub fuels. Dead fuel moisture content was the most important determinant of ignition success, along with species, type of ignition source and wind speed. Field experiments were recommended to complement the laboratory results.

Weise *et al.* (2005) and Zhou *et al.* (2005; , 2007; , 2005) conducted experiments in the laboratory using four common chaparral shrub species to model conditions for marginal burning in these fuels. They investigated the roles of slope, fuel load and arrangement, live fuel moisture content, air temperature, relative humidity and wind speed on fire spread thresholds. Models based on logistic regression (Weise *et al.*, 2005; Zhou *et al.*, 2007; Zhou, Weise *et al.*, 2005) and numerical modelling (Zhou, Mahalingam *et al.*, 2005) approaches included from four to six predictor variables, with live fuel moisture content, slope and a measure of the fuel properties (either load or arrangement) common to all four models. Weise *et al.* (2005) and Zhou *et al.* (2007) also found differences between the four species that were tested. However, Fletcher *et al.* (2007) found that live fuel moisture content had almost no influence on time to ignition and ignition temperature in Californian chaparral and Utah shrub fuels. Further work explored the effect of crown fuel bulk density on crown fire initiation from surface fires (Tachajapong *et al.*, 2008).

Small-scale experiments have been carried out in the field in some shrub communities. Early work by Bruner and Klebenow (1979) in pinyon-juniper communities (comprising *Pinus monophylla* and *Juniperus osteosperma*) of Nevada linked spread success to air temperature, wind speed and vegetation cover. More recently, Fernandes *et al.* (2008) determined thresholds for sustainability of surface fires in *P.pinaster* stands in northern Portugal with an understorey of *U.minor*, and found the moisture content of fine dead fuels to be highly significant. This moisture content threshold varied significantly, but a general value of 35% was determined to represent the boundary between sustained fire spread and extinction. Research into fire behaviour in Calluna-dominated heathlands in Scotland found that the moisture content of both live and dead fine fuels was important for ignition and development of self-sustaining fires (Davies & Legg, 2008; Davies *et al.*, 2006). Pellizzaro *et al.* (2007) focussed on modelling ignitability or fire spread success based on annual variations in live fuel moisture content in Mediterranean shrub fuels, and also found differences in ignitability between shrub species.

Larger-scale field experiments have been carried out in Australia in the last two decades. In Eucalypt mallee vegetation with a heath understorey, McCaw *et al.* (1995) found that the moisture content of the surface litter was the most critical variable that determined fire propagation. Recent studies in Australia modelled fire spread success in similar mallee-heath fuels using wind speed, fuel characteristics and the moisture content of the near-surface fuel layer (Cruz & Gould, 2008). Near-surface fuels are a layer up to 1 m above the litter comprising low shrubs, grasses and suspended leaf, twig and bark material from the overstorey (Gould, McCaw, Cheney, Ellis, Knight *et al.*, 2007; Gould, McCaw, Cheney, Ellis, & Matthews, 2007). A near-surface fuel layer was also described in Tasmanian buttongrass moorlands at heights from 15-50 cm, although most of the dead fuel occurs in clumps 10-30 cm above the ground surface. The moisture content of this layer was important in determining thresholds at which fires would self-extinguish (Marsden-Smedley *et al.*, 2001). The dead fuel moisture of extinction (the level of dead fuel moisture beyond which a fire will no longer be sustained) was found to be exceptionally high, at approximately 70% (Marsden-Smedley & Catchpole, 1995b). This was considerably higher than the fibre saturation point of fuels of around 35% (Cheney, 1981) and also considerably higher than the moisture of extinction for most dead forest fuels, generally from 25% to 40% (Chandler *et al.*, 1983; Luke & McArthur, 1978; Woodman & Rawson, 1982).

2.5. Fire danger rating

Effective fire management requires an understanding of the fire environment. The fire environment refers to 'the surrounding conditions, influences and modifying forces of topography, fuel and fire weather that determine the behaviour of a fire' (Countryman, 1972). Most countries have either developed or adopted fire danger rating systems to support fire management decision-making.

Fire danger is defined as "a general term used to express an assessment of both fixed and variable factors of the fire environment that determine the ease of ignition, rate of spread, difficulty of control, and fire impact" (Merrill & Alexander, 1987). Fixed fire danger factors such as topography, assets, climate and fuels are relatively constant temporally, but can vary spatially. Variable fire danger factors vary temporally (hourly, daily, seasonally). Weather is a variable factor, as is the condition of the vegetation (e.g. curing/proportion dead, moisture content). Fire danger can be regarded as the potential for damage by fire (Countryman, 1966).

A fire danger rating system integrates the fixed and variable fire environment factors and produces qualitative and/or numerical indices of fire potential. All fire danger rating systems have the common objective to produce a simple measure to assess and compare the flammability of fuels from day to day (Chandler *et al.*, 1983; Stocks *et al.*, 1989). Fire danger rating therefore indicates the expected burning conditions (i.e., likelihood of ignition, potential fire rate of spread, fire intensity, fire size and shape) over an area for a given time period, usually the afternoon peak burning period when fuels are at their driest and weather conditions are most conducive to high fire potential. Variables such as topography and fuels are often generalised across the areas to which the rating is applied. The outputs (codes or indices) are usually relative or dimensionless (Allgöwer *et al.*, 2003). This is different from a fire behaviour forecast, which provides an estimate of expected fire behaviour for an active wildfire over a specified period at a specific point on the landscape. A fire behaviour forecast is specific to fuels and topography in the area of the wildfire (Chandler *et al.*, 1983; Fujioka *et al.*, 2009). Outputs from fire behaviour forecasts are physical descriptions of the fire characteristics, such as rate of forward spread ($m\ h^{-1}$), flame height (m) and fire intensity ($kW\ m^{-1}$).

Fire danger rating systems produce one or more qualitative and/or numerical indices and classes of ignition potential and probable fire behaviour. These are used as guides in a variety of fire management activities, such as (refer Brown & Davis, 1973; Chandler *et al.*, 1983; Taylor & Alexander, 2006):

- prevention planning (fire danger warnings, access and activity controls in high-risk areas, fire permit issue and restrictions, fire bans);
- preparedness planning (determining levels of suppression resources required and/or standby arrangements);
- detection planning (lookouts, aerial patrols);
- suppression tactics and strategies for active wildfires;
- prescribed burn planning.

The fire danger rating system therefore provides a suite of critical information to the fire manager. Fire danger rating system outputs also serve to inform the public, indicating fire danger levels in an area (Luke & McArthur, 1978). For the general public, the colour-coded fire danger boards on roadsides are the most obvious outputs from a fire danger rating system. The selection of the fire danger rating area is also important, and it must have a uniform climate. Changes in weather and climate within the area will lead to differences in fuel moisture, and hence fuel flammability and fire behaviour, rendering outputs from the system invalid in some parts of the rating area (Chandler *et al.*, 1983).

2.5.1. Principles

Deeming *et al.* (1974) stated that any fire danger rating system must provide accurate and reliable estimates of the potential ease of ignition, rate of spread and rate of combustion. These three variables provide essential information for fire suppression. Nelson (1955) described five general principles of a fire danger rating system:

i. Systems must have a simple method of measuring important variables and integrating these variables into numerical values.
ii. Standards for fire weather station location and instrumentation must be adhered to.
iii. Fire weather observers must be properly trained.
iv. Fire weather stations need to be inspected regularly.
v. Continuity of fire weather and fire danger records is essential.

The five key components that should form the basis of a fire danger rating system are (NWCG, 2002):

i. Models representing the relationships between fuels, weather, topography and the impact on fire management.
ii. A method or system for gathering data required as inputs for the system.
iii. A system to process the inputs into ratings (outputs).
iv. A communication system to disseminate the fire danger rating outputs.
v. A data storage system to allow for long-term analyses and reference.

Taylor and Alexander (2006) provide a comprehensive overview of fire danger rating system principles and also emphasise the importance of not applying systems beyond the conditions (or environments) to which they are applicable. They also highlight the need to correlate system outputs with actual fire occurrence and severity.

2.5.2. History

The earliest research into fire danger rating started in 1922 in the United States (Gisborne, 1936) and in 1925 in Canada (Stocks *et al.*, 1989). This led to comprehensive and different systems of rating fire danger in these two countries. Development of fire danger rating systems in Australia commenced in the 1930's (San-Miguel-Ayanz *et al.*, 2003). A number of fire danger rating systems have subsequently been developed around the world. However, it was largely in North America, Australia and the former USSR that fire danger rating systems originated (Chandler *et al.*, 1983). This was probably because these countries have climates conducive to wildfires with the potential to burn large areas and cause significant damage, and also because they all experienced a rapid growth in the forest industry at the turn of the twentieth century. This necessitated organised approaches to fire control and management.

Many of the systems in use in other countries are modifications of the two North American systems, the United States National Fire Danger Rating System and the Canadian Forest Fire Danger Rating System. Major differences between these two systems lie in the approaches taken in their development (theoretical versus largely empirical). A major disadvantage of many fire danger rating systems is that they have been developed with incomplete knowledge of the fire danger conditions they are intended to cover, leading to problems with operational credibility of the systems (Cheney, 1988).

2.5.3. Current fire danger rating systems

A number of fire danger rating systems are used around the world, ranging from quite complex systems that account for a range of fuel and environmental factors to systems that are very simple, requiring only basic inputs of temperature and relative humidity.

The Canadian and United States fire danger rating systems have been adopted and modified for use in many countries. This is largely because of the comprehensive development and operational use of these systems over a long period of time. Adopting an existing system and validating it to local fire environment conditions can be a cost-effective and simple means of implementing a fire danger rating system. By comparison, developing new fire danger rating systems can be time-consuming and costly. However, problems associated with implementing existing systems elsewhere include applying systems to fuel types and potential ranges of fire behaviour beyond those for which the systems were developed (Fogarty *et al.*, 1998; Taylor & Alexander, 2006).

2.5.3.1. United States

Research into fire danger rating in the United States began in 1922 (Gisborne, 1936). This resulted in the development of a range of meters, indices and slide rules from 1930 to 1950 (Fujioka *et al.*, 2009; Hardy & Hardy, 2007). Each of these systems was developed separately for different regions of the USA, and by 1954 eight different systems were in use across the country (Deeming *et al.*, 1974; NWCG, 1985). A coordinated research effort led to the development and implementation of the National Fire Danger Rating System (NFDRS) in 1972 (Deeming *et al.*, 1974). The NFDRS was updated in 1978 (Deeming *et al.*, 1977), with further revisions in 1988. The revisions improved the applicability of the 1978 version of the NFDRS to the more humid eastern areas of the USA. This included a new set of 20 fuel models, and the addition of the Keetch-Byram Drought Index (KBDI)[5] to increase the amount of dead fuel with ongoing drought (Burgan, 1988; Keetch & Byram, 1968). Rothermel's fire spread model (Rothermel, 1972) forms the core of the NFDRS. Rothermel's model is not specific to a fuel type, and requires the input of fuel-specific information. This input process is simplified through selecting an appropriate fuel model. There are a total of 20 fuel models in the NFDRS, with a range of descriptors associated with each model. These 20 fuel models are intended to broadly represent the major fuel complexes across the USA (Burgan, 1988; Deeming *et al.*, 1977)

[5] The Keetch Byram Drought Index (KBDI) is an index that measures drought in terms of the amount of precipitation required to recharge the soil to field capacity (Keetch & Byram, 1968).

The NFDRS is largely based upon the physics of moisture exchange and heat transfer, with little empirical or statistical basis (Deeming *et al.*, 1974). This feature of the NFDRS distinguishes it from the Canadian[6] and Australian systems, which are largely empirically based on extensive field experiments and data collection.

There is a clear difference between the NFDRS and the Fire Behavior Prediction System (FBPS), which are complementary systems (Andrews, 1988; NWCG, 1985). The NFDRS is applicable for large area fire danger rating and planning, whilst the FBPS caters for site-specific fire behaviour prediction, taking account of site-specific fuel, weather and topography information.

Four components form the basis of the NFDRS (Figure 2.1):

1. The Ignition Component (IC) – related to the probability of a firebrand producing a fire that will require suppression action.
2. Risk components – made up of the Lightning Risk (LR), an indication of lightning occurrence and "efficiency", and the Man-Caused Risk (MCR), an assessment of the status of man-caused fire sources.
3. Spread Component (SC) – indicating the forward rate of spread of a fire.
4. Energy Release Component (ERC) – the estimated potential available energy released per unit area in the flaming zone of a fire.

A further four indices are provided to aid fire management activities (Figure 2.1):

1. Man-caused fire occurrence index (MCOI) – derived from Man-Caused Risk and the Ignition Component.
2. Lightning-caused fire occurrence index (LOI) – derived from the Ignition Component and Lightning Risk.
3. Burning Index (BI) – derived from the Energy Release Component and the Spread Component. The BI is linearly related to the length of flames at the head of the fire.
4. Fire load Index (FLI) – combines the Burning Index with the probable number of fires estimated from the Man-caused fire occurrence index and the

[6] A comparison of the US and Canadian fire danger rating systems is contained in Van Wagner (1975).

Lightning-caused fire occurrence index. The FLI integrates risk, ignition and fire behaviour potential as indicated by the other indices and components.

Fuel moisture, wind and risk are the primary variables that account for day-to-day variation in fire danger (Deeming *et al.*, 1974). There are four classes of dead fuels, based on the moisture content response of individual fuel particles to changes in relative humidity (the timelag). These are the 1-hour, 10-hour, 100-hour and 1000-hour timelag fuels. There are also two live fuel classes: grasses and other herbaceous plants; and shrubs (twigs and foliage). The effect of live fuels on fire behaviour and seasonal variations in live fuel moisture content are incorporated in the system (Burgan, 1979). The effect of wind on fire danger is accounted for by integrating wind, slope and fuel properties into the Spread Component (Deeming *et al.*, 1977). Risk is evaluated by the Lightning-caused and Man-caused fire occurrence indices, which combine information on the likelihood of lightning and man-caused ignition factors with the Ignition Component (Deeming *et al.*, 1977).

The United States NFDRS has also been evaluated in other countries, such as South Africa (Bridgett *et al.*, 2003; Van Wilgen, 1984; Van Wilgen & Burgan, 1984) and Mediterranean areas of Europe (e.g., Ruiz *et al.*, 2002; San-Miguel-Ayanz *et al.*, 2003; Sithoe, 2007)

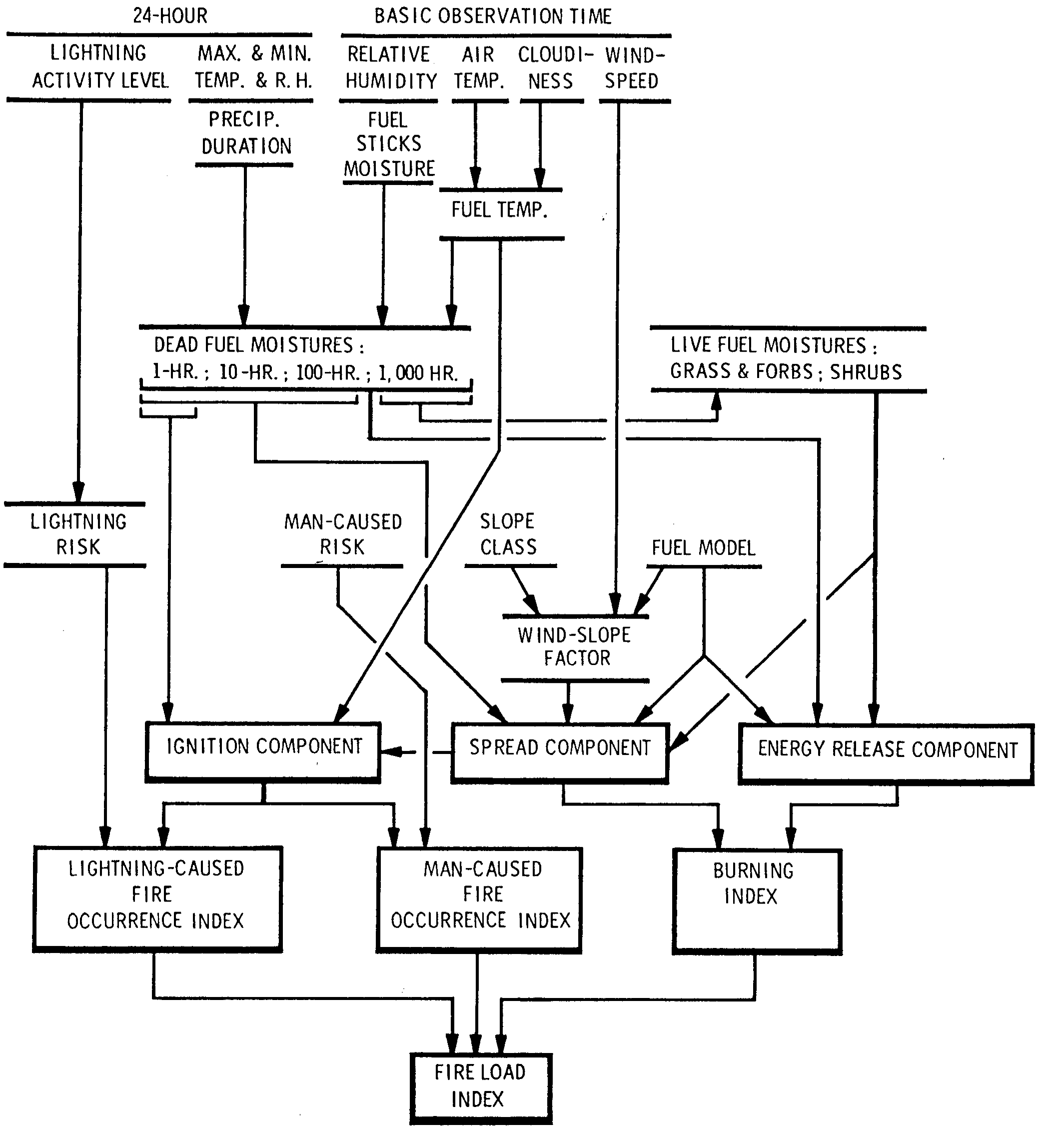

Figure 2.1. Structure diagram of the US NFDRS (Deeming *et al.*, 1977).

2.5.3.2. Australia

Development of fire danger rating systems in Australia commenced in the 1930's, with a basic system based on the moisture content of dowel sticks (San-Miguel-Ayanz *et al.*, 2003). In 1958 the McArthur Fire Danger Rating System for dry sclerophyll forests was introduced, based on data from 89 experimental fires from a range of weather conditions (McArthur, 1958). Head fire rate of spread was correlated with the surface moisture content of fine fuels and wind speed, and a rating provided of suppression difficulty. This is an empirical system, based on meteorological inputs only. The scale of the fire danger index (FDI) ranges from 0 to 100 (Luke & McArthur, 1978). Fire danger classes are derived from the FDI scale and represent the degree of difficulty of suppressing a fire in the eucalypt litter fuel type with a fuel load of 12.5 t ha^{-1} (Cheney, 1988).

A number of improvements have been made to the system, including accounting for the effects of long-term drought using the Keetch-Byram Drought Index from the USA (Keetch & Byram, 1968). The system is still widely used throughout eastern and southern Australia. Despite some limitations in applicability to the range of fuel and fire environments in Australia, the system is largely regarded as reliable for broad-scale fire danger rating purposes when combined with local interpretation (San-Miguel-Ayanz *et al.*, 2003).

McArthur also introduced a fire danger rating system for grasslands in 1960, using fine fuel moisture content and wind speed (McArthur, 1960). In 1966, a circular slide rule was introduced to estimate the fire danger in grasslands (the Mark III version) using the degree of grassland curing[7], temperature, relative humidity and wind speed. The current revised system, the Mark V Grassland Fire Danger Rating System, was introduced in 1977, with some minor modifications and incorporating the effects of grass fuel load on fire behaviour (Cheney, 1988; Cheney & Gould, 1995b; Luke & McArthur, 1978).

[7] The degree of curing of a grassland fuel complex represents the fraction of dead material present in the grass sward (Cheney & Sullivan, 1997). It is typically expressed as a percentage.

In Western Australia, a separate system of rating fire danger in jarrah (*Eucalyptus marginata*) and karri (*Eucalyptus diversicolor*) forests and pine plantations was developed – the Forest Fire Behaviour Tables for Western Australia. This is an empirically-based system that provides estimates of fuel moisture content and head fire rate of spread for six standard structural forest fuel types common in the southwest of Western Australia (Burrows & Sneeuwjagt, 1988; Cheney, 1988). It uses a bookkeeping system to estimate the moisture content of the litter in a similar manner to Canadian system described next.

2.5.3.3. Canada

Research into forest fire danger rating commenced in Canada in 1925 (Van Nest & Alexander, 1996). The coordinated development of the national Canadian Forest Fire Danger Rating System (CFFDRS) commenced in 1968. The CFFDRS is based on four modules or subsystems (Figure 2.2):

- Fire Weather Index (FWI) System;
- Forest Fire Behavior Prediction (FBP) System;
- Fire Occurrence Prediction (FOP) System;
- Accessory Fuel Moisture System.

The two major subsystems used are the Fire Weather Index and Fire Behavior Prediction Systems (Taylor & Alexander, 2006). The Fire Occurrence Prediction and Accessory Fuel Moisture Systems are not yet complete (Fujioka *et al.*, 2009; San-Miguel-Ayanz *et al.*, 2003). The CFFDRS is empirical and based on extensive data collection over many years. Physical theory was applied in the development of algorithms and to supplement ‘empirical gaps’ (Van Wagner, 1998).

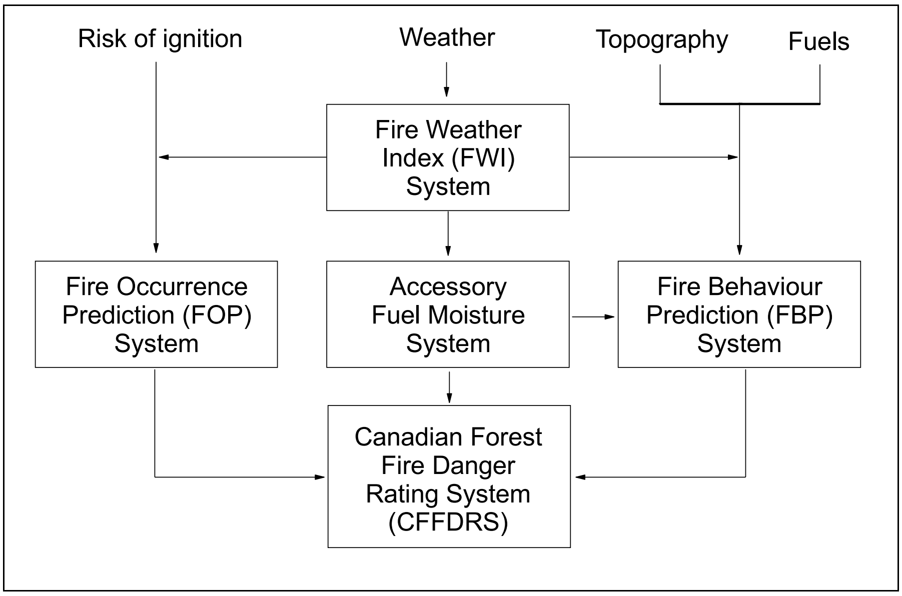

Figure 2.2. Simplified structure diagram of the Canadian Forest Fire Danger Rating System (adapted from Stocks *et al.* 1989).

The Fire Weather Index (FWI) System (Figure 2.3) forms the core of the CFFDRS, and consists of six relative numerical ratings for different aspects of fire danger. It is based on a reference fuel type, mature jack (*Pinus banksiana*) and lodgepole (*Pinus contorta*) pine stands on level terrain. Basic inputs are four weather observations (temperature, relative humidity, wind speed at 10 m and 24-hour accumulated rainfall) measured at noon (standard time) each day. The numerical ratings are intended to represent fire danger conditions during the peak fire danger period, generally around 16:00. The three fuel moisture codes, and the moisture contents of the fuel layers they represent, are (Van Wagner, 1987; Wotton, 2008):

- Fine Fuel Moisture Code (FFMC) – fine surface litter;
- Duff Moisture Code (DMC) – loosely compacted duff of moderate depth;
- Drought Code (DC) – deep compact organic matter.

These fuel moisture codes act as bookkeeping systems, adding moisture after rain and subtracting moisture for each day's drying. The codes have built-in time lags and rainfall thresholds (below which the precipitation will not lower the value of the code) for the particular fuel layer represented. Higher values of these three fuel moisture codes correspond to lower moisture contents (Stocks *et al.*, 1989; Wotton, 2008).

The three fuel moisture codes and wind speed are linked in pairs to form two intermediate and one final index of fire behaviour (refer Figure 2.3):

- Initial Spread Index (ISI) – combines the effect of wind speed and fine fuel moisture content (represented by the Fine Fuel Moisture Code), providing a numerical rating of fire spread rate (without the influence of fuel quantity);
- Buildup Index (BUI) – combines the Duff Moisture Code and Drought Code and represents the total amount of fuel available for combustion;
- Fire Weather Index (FWI) – combines the Initial Spread Index and Buildup Index to indicate the intensity of a spreading fire (on level terrain).

The FWI System provides a general indication of various aspects of fire activity and is best used as a general measure of fire danger (Stocks *et al.*, 1989). Different components of the FWI System can also be used to delineate different fire danger classes (Stocks *et al.*, 1989).

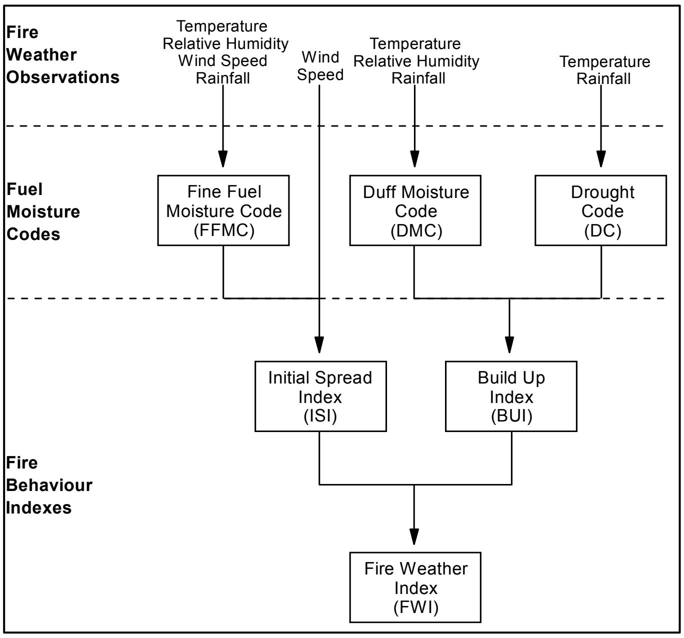

Figure 2.3. Structure diagram of the Fire Weather Index System (Van Wagner, 1987).

The Fire Behavior Prediction System has a number of primary and secondary outputs that describe fire behaviour characteristics (e.g., head/flank/back fire rate of spread and spread distance, fire intensity, area, perimeter, etc.). This system takes account of variations in fuel type and topography not accounted for in the FWI System. There are 16 fuel types that represent the major fuel complexes across Canada. Fire behaviour is determined using fuel type models based on FWI components and slope steepness, where applicable (Forestry Canada Fire Danger Group, 1992).

The CFFDRS has been implemented in whole or in part in a number of countries, including New Zealand, Fiji, Mexico, southeast Asia, Portugal, Spain, Sweden, United Kingdom and the US states of Alaska, Michigan and Minnesota (de Groot *et al.*, 2007; de Groot *et al.*, 2005; Kitchen *et al.*, 2006; San-Miguel-Ayanz *et al.*, 2003; Taylor & Alexander, 2006; Van Nest & Alexander, 1996).

2.5.3.4. New Zealand

Following reviews of the US National Fire Danger Rating System, the Canadian Forest Fire Danger Rating System and the McArthur Mk4 Forest Fire Danger Meter, New Zealand adopted the Canadian Forest Fire Danger Rating System and introduced the Fire Weather Index System for fire danger rating in coniferous plantation forests in 1980. The FWI System was favoured over the other systems because (Valentine, 1978):

1. It is easy to use and understand;
2. The system is based on sound scientific principles;
3. It has outstanding interpretive backup (through extensive validation and operational implementation);
4. It was developed in boreal pine forest (the priority for fire danger rating in New Zealand at the time being protection of plantation forests of predominantly *Pinus radiata*);
5. The system had been applied with success in the maritime climates of British Columbia, similar to the maritime climate of New Zealand.

Other than this implementation of the FWI System in 1980, no further validation or extension of the CFFDRS to New Zealand fuel types took place until a rural fire research programme was established in 1992 (Alexander, 1992-93; Fogarty *et al.*, 1998). A major focus of the research programme since then has been to adapt the CFFDRS to New Zealand fuel types (including shrubland, tussock grassland, wetlands, and crop stubble) to develop the New Zealand Fire Danger Rating System (NZFDRS). The NZFDRS has the same structure as the CFFDRS (refer to Figure 2.2).

A fire danger class scheme was derived from the NZFDRS, using head fire intensity to define the classes in terms of fire potential and implications for fire suppression (Alexander, 2008). Five fire danger classes are used to provide fire danger ratings for forest, grassland and shrubland areas in New Zealand (Table 2.1).

Table 2.1. The five fire danger classes used in New Zealand, defined by head fire intensity. Detailed descriptions of fire potential and implications for fire suppression for each class are contained in Alexander (2008).

Fire Danger Class	Colour	Head Fire Intensity (kWm^{-1})	Description
Low	Green	≤10.5	Fires do not spread beyond their point of origin; if they do, control is easily achieved with hand tools.
Moderate	Blue	10.6 – 500.5	Creeping surface fire activity. Direct manual attack around the perimeter with hand tools.
High	Yellow	500.6 – 2000.5	Running/vigorous surface fires. Control becomes more difficult if not achieved early after ignition, and requires water under pressure and/or heavy machinery.
Very High	Orange	2000.6 – 4000.5	Burning conditions critical. Intense surface fires, torching and intermittent crowing in forests possible. Head fire attack only possible with aircraft.
Extreme	Red	≥4000.6	Situation is 'explosive'. Violent physical fire behaviour possible. Fires can pose serious threat to life and property. Very difficult if not impossible to control, effective suppression action limited to back and flanks.

2.5.3.5. Other

The Nesterov Index (Nesterov, 1949) was developed in Russia (former USSR). This is a simple ignition index and indicates the chance of a fire starting in a particular area. It is calculated from the number of days since last rainfall greater than 3 mm, temperature and dew point temperature. Each time rainfall of greater than 3 mm is recorded, the index drops back to zero. Danger classes are determined based on different values of the ignition index, and adjusted for different regions based on 10 years of fire statistics and the values of the index (Chandler *et al.*, 1983; Groisman *et al.*, 2007; Loboda, 2009). A modified version of this index was used in Portugal (Fujioka *et al.*, 2009; Viegas *et al.*, 1999).

The Ångström Index in Sweden is used as an indicator of expected fire starts in parts of Scandinavia (Chandler *et al.*, 1983), and was also used in Portugal from 1970 to 1986 (Fujioka *et al.*, 2009). It is a very simple system, based on temperature and relative humidity (Lin, 2000). Effects of precipitation and wind are ignored, and the relationship with fuel moisture is not adequately modelled. Values of the index are categorised to provide an indication of fire occurrence within the rating area (Chandler *et al.*, 1983). In France, a method known as the Numerical Risk is based on daily values of temperature, relative humidity, cloud cover, wind speed, and an initial value of the soil water content (Drouet & Sol, 1993; Sol, 1990; Viegas *et al.*, 1999). An Italian method (Bovio *et al.*, 1984) combines loss of water in the soil due to actual evapotranspiration with potential evapotranspiration to calculate a fire danger index (Viegas *et al.*, 1999). A Spanish method (ICONA, 1988) evaluated the probability of a fire start based on temperature and relative humidity. All of the above methods yield indices, the values of which are used to determine fire danger classes (Viegas *et al.*, 1999).

A more recent development in Europe has been the establishment of the European Forest Fire Information System[8] (Camia *et al.*, 2006). This system provides ratings of fire danger across Europe for one to six days. The fire danger classes are determined using the Canadian Fire Weather Index System, with some modifications to the underlying algorithms.

[8] http://effis.jrc.ec.europa.eu/, accessed 10 April 2009

2.5.4. Analysis of fire danger rating system approaches

Fire danger rating systems are designed to provide a broad-area rating of fire danger in terms of expected burning conditions. These outputs are used for public information and area-based fire management. Fire behaviour prediction systems indicate fire behaviour at the site-specific level, for actual fires on the landscape (Chandler *et al.*, 1983). The three major fire danger rating systems in use around the world are the United States, Canadian and Australian systems. The Canadian Forest Fire Danger Rating System (CFFDRS) is fundamentally different to the US National Fire Danger Rating System (NFDRS). The Canadian system has largely been derived from empirical data collected in the field, incorporating some basic physical models. The US National Fire Danger Rating System was derived from a largely theoretical approach, using complex physical modelling and laboratory experiments (Deeming *et al.*, 1974; Van Wagner, 1975).

Fire danger rating systems developed using a theoretical approach have the advantage that the theories of fire dynamics and fuel moisture exchange can be applied to any fuel type or fire environment. However, a disadvantage is that applying the component models to other fuel types and fire environments can be difficult due to the requirement for description and quantification of the fuel characteristics. The reliability of outputs can also be questioned when these systems that are derived from laboratory experiments on a small scale are used for broad area fire danger rating. Systems developed using the empirical approach have the advantage in that they have been developed from field data under ‘real world’ conditions. They generally perform well if applied to the conditions similar to those under which they were developed. A disadvantage is that they cannot be extended to fire environment conditions beyond their original basis without further adaptation. Regardless of the type of fire danger rating system implemented, it is essential that users have a sound understanding of the assumptions underlying these systems, and the limitations of the systems (beyond which the outputs can be questionable).

Another significant difference between the US and Canadian systems is the separation between fire danger rating and fire behaviour prediction. The US NFDRS completely separates the fire danger rating and fire behaviour prediction systems, and they are determined through different inputs and computations (Andrews, 1988; Scott & Burgan, 2005). The Canadian system does distinguish between fire danger rating and fire behaviour prediction to some extent, but not as clearly as the US system. The Canadian system uses the FWI System indices for broad-area fire danger rating in benchmark fuel types and the FBP System to provide site-specific fire behaviour prediction. However, the inputs for the FBP System rate of spread models are based on correlations between observed rate of fire spread and FWI System indices from experimental burns and wildfires. The two systems are therefore not as distinct as in the US system. With an inadequate understanding of the different purposes of the fire danger rating and fire behaviour prediction systems, confusion can arise when trying to separate broad-area fire management from site-specific fire behaviour prediction.

The two major forest fire danger rating systems in Australia, the McArthur Forest Fire Danger Rating System and the Western Australia Forest Fire Behaviour Tables, also do not clearly separate fire danger and fire behaviour (Burrows & Sneeuwjagt, 1988; Cheney, 1988; Luke & McArthur, 1978; San-Miguel-Ayanz *et al.*, 2003; Sneeuwjagt & Peet, 1998). However, the results of the Project Vesta fire behaviour experiments in dry Eucalypt forest have led to improvements in forest fire behaviour models and may result in some separation of the elements of fire danger rating and fire behaviour prediction for eucalypt forest fuels (Gould, McCaw, Cheney, Ellis, Knight *et al.*, 2007). Revisions to grass fire spread models in Australia have resulted in the separation of fire behaviour and fire danger rating (Cheney & Gould, 1995a; Cheney, 1998; Cheney & Sullivan, 1997).

The more widely used systems are those that integrate a larger number of the factors influencing fire danger, rather than those that are based on one or two simple meteorological inputs only. For this reason, the US and Canadian systems are the most popular.

2.5.5. Current methods of rating fire danger in shrub fuels

Few fire danger rating systems have been developed to provide specific fire danger rating assessments for shrub fuels. In most cases, existing systems for forest or grasslands have been applied with minor modifications to cater for shrub fuels. Existing systems to cater for forests or grasslands have also been applied to shrub fuels with no modifications.

2.5.5.1. United States

Of the 20 fuel models that form part of the US NFDRS, up to five models are applicable to shrub fuel types. These models include chaparral, sagebrush, pocosin, scrub oak and Alaskan shrub species. This is the only major fire danger rating system that contains specific fuel models for shrub fuels. The BEHAVE System (for predicting fire behaviour) allows for unique fuel models to be developed using certain fuel characteristics. However, fuel models developed in the BEHAVE system for site specific fire behaviour prediction cannot be used in the NFDRS (Burgan & Rothermel, 1984). In many shrub fuels in the US live fuel moisture content is an important factor influencing fire behaviour or flammability. Profiles of long-term trends in seasonal live fuel moisture content in southern California have been used for fire danger assessments and to compare current fire danger relative to previous seasons' fire danger levels (Weise *et al.*, 1998). It is difficult to extend the NFDRS to other countries because of the extensive work to classify and determine the fuel characteristics to tailor the fuel models to fit shrubland fuels (e.g., Viegas *et al.*, 1999; Xanthopolous, 2002).

2.5.5.2. Australia

The McArthur Forest and Grassland Fire Danger Rating Systems are used to rate fire danger in eastern areas of Australia. The Forest Fire Behaviour Tables form the basis of the fire danger rating system for jarrah, karri and pine plantation forests in Western Australia. None of these systems have been found to be appropriate for rating fire danger and expected fire behaviour in shrubland fuels, although they are still applied to these fuel types in many areas in the absence of an alternative.

Significant research has been carried out in Australia to understand and describe fuels and fire behaviour in shrublands, such as fuel moisture modelling, fuel characteristics, flammability and ignition thresholds (e.g., Catchpole *et al.*, 2001; Catchpole *et al.*, 1998; Marsden-Smedley & Catchpole, 1995a, 1995b, 2001; Marsden-Smedley *et al.*, 2001; McCaw, 1997; Pippen, 2007; Plucinski & Anderson, 2008). However, the only unique system for fire danger rating in Australian shrub fuels is that developed for Tasmanian buttongrass moorlands (Marsden-Smedley *et al.*, 1999). The Moorland Fire Danger Rating is a dimensionless index indicating the degree of suppression difficulty on a scale from 0 (fires will not sustain) to 100 (extreme fire danger). It is predicted from head fire spread rate, which is in turn derived from wind speed, fuel age (5, 10 or 20+ years) and dead fuel moisture content. This system was empirically derived through data from experimental burns, prescribed burns and wildfires.

Krusel *et al.* (1993) attempted to develop a new model to predict days of high fire activity in mallee shrubland in north-western Victoria to replace the McArthur systems. The model was based on meteorological observations, and developed through analysis of historic fire records, fire danger indices and meteorological data. Using five meteorological variables slightly improved accuracy for prediction of high fire activity days over the McArthur System. However, accuracy was still low. There are also difficulties with the use of analyses of historic fire occurrence, since factors causing fires (particularly human factors) can change over time.

2.5.5.3. New Zealand

The New Zealand Scrubland Fire Danger Rating model was developed and released for operational use in 2000 (Anderson, 2009; Pearce, 2000a). This model employs the same approach as that for the Forest and Grassland Fire Danger Rating models. It has five fire danger classes based on head fire intensity (Table 2.1). However, fire danger is determined using wind speed (measured at 10 m above the ground in an open clearing) and the Fine Fuel Moisture Code (FFMC) of the Fire Weather Index System. A standard fuel load of 20 t ha^{-1} is assumed for all shrub fuels across the country. There is also a threshold FFMC value of 60, below which fire danger is always 'Low'. The purpose of this FFMC threshold is to represent the boundary between ignition success and failure. This is based on limited observations from experimental fires. A complete description of the derivation of the Scrubland Fire Danger Rating model is provided in Chapter 7 (Section 7.1).

2.5.5.4. Europe and other countries

Shrub vegetation is widespread throughout Europe, particularly in the Mediterranean areas and western Europe. Fire plays a major role in most of these shrublands, and many of these European landscapes have been maintained by fire for farming purposes (Di Castri, 1981; Gimingham & Chapman, 1979).

There are a number of fire danger rating systems used in southern Europe. These fire danger rating systems are applied to a range of fuel types without distinguishing different fire danger levels for the different fuels. The four main four approaches (Portuguese, French, Italian and Spanish) and the Canadian Fire Weather Index (FWI) System were evaluated by Viegas *et al.* (1999). These systems were compared against the daily number of fires and area burned over periods from 3-9 years from six different regions in France, Italy and Portugal. Although vegetation types burned were not separated in the data, it could be assumed that a significant proportion of the data would have included fires in shrub fuels. Only the Canadian and Portuguese (based on a modified Nesterov Index from Russia) systems predicted the number of fires and area burned well. A recent method was suggested to determine fire danger for shrublands and grasslands of central Spain derived levels of ignition potential from 0 (unlikely) to 1 (likely) from live and dead fuel moisture content. Dead fuel moisture content was calculated from the US NFDRS 10-hour fuel moisture code based on field validation, and live fuel moisture was derived from satellite imagery (Chuvieco, Aguado *et al.*, 2004). As previously mentioned, there has been a significant focus on evaluating the performance and applicability of the Canadian Fire Weather Index System in Southern Europe (Manta *et al.*, 2002; Rainha & Fernandes, 2002; Rodriguez y Silva, 2002; San-Miguel-Ayanz *et al.*, 2003; Viegas *et al.*, 2001).

In the United Kingdom, recent work has focussed on developing models to predict fire behaviour and fire danger rating in heather moorland fuel complexes dominated by *Calluna vulgaris*. The Met Office Fire Severity Index (MOFSI) is based on seasonally adjusted values of the Canadian Fire Weather Index System and is used operationally. However, problems with its applicability to heather moorlands include the inability to predict periods of flammability or high fire risk when fuels reach very low moisture contents at low temperatures due to frost or ice desiccation of live fuels. Further validation and modification is also required to apply the system across a range of UK fuel complexes, including other shrub fuels such as gorse (*U.europaeus*) and grassy moorlands (Davies & Legg, 2008; Davies *et al.*, 2006; Kitchen *et al.*, 2006).

In South Africa, the US National Fire Danger Rating System was adapted for fire danger rating in fynbos. A fuel model was developed using fynbos-specific parameters, such as fuel load by fuel class, moisture content, fuel mineral content, fuel bed depth, surface-area-to-volume ratios, fuel energy and ash content. The fynbos fuel model was not tested in the field and there was a lack of wildfire data to test the model. It was compared with the NFDRS chaparral fuel model and significant differences were observed. Chaparral fuels have heavier fuel loads, greater fuel bed depth, and a lack of herbaceous vegetation compared to fynbos. This caused differences in predicted rates of spread for the two fuel types (Van Wilgen, 1984). However, an analysis of historic fire danger using the NFDRS showed that fire size correlated well with periods of high fire danger (Van Wilgen & Burgan, 1984).

2.6. Discussion

Shrubland fuels differ markedly from forest and grassland fuels. The most significant difference is the ability for fires in shrub fuels to rapidly develop into extremely high-intensity and fast-moving fires that can pose significant risks to life and property. This is mostly due to shrub fuels supporting large amounts of dead elevated fine fuel that dry rapidly, the presence of chemical compounds in the foliage that enhance flammability, and the contribution of live foliage to combustion. Many shrubland fuel complexes are also adapted to and dependent upon fire.

Despite these differences, many fire danger rating systems applied to shrubland-dominated areas were originally developed for use in forest and grassland fuels. In some cases they have been applied to shrub fuels with little or no modification. This is mostly because development of fire danger rating systems originated in countries with a focus on protection of forest resources from fire. There are definite benefits in adopting and refining existing fire danger rating systems for use in other countries and fire environments, particularly in terms of cost and research effort (Fogarty *et al.*, 1998). However, it is not appropriate to simply apply empirically-derived systems (such as the Canadian and Australian systems) to conditions beyond those under which the original system was developed without modification or validation. An empirical system also does not readily lend itself to major changes in the underlying relationships. On the other hand, systems derived from largely physical or conceptual approaches (such as the US system) can have their applicability to 'real world' conditions questioned. To apply these systems to other fuel types can also require considerable research effort to describe and quantify fuel characteristics.

However, before existing fire danger rating systems are applied to shrub fuels, it is important that the fundamental concepts of fire behaviour in shrub fuels are understood. There remain significant gaps in the knowledge and ability to model fire behaviour in shrub fuels. The effect of fuel moisture on fire behaviour is not well understood. Live fuel moisture content can significantly influence fire behaviour in shrub fuels (Davies & Legg, 2008; Davies *et al.*, 2006; McCaw, 1997; Weise *et al.*, 2005), yet the ability to model live fuel moisture by accounting for physiological and environmental influences is limited (Weise *et al.*, 1998). Even the influence of dead fuel moisture on shrub fire behaviour is not clear. Models of fire behaviour in a variety of shrubland fuels in different countries have shown contradictory results, with fuel moisture significant in some studies (Baeza *et al.*, 2002; Fernandes, 2001; Marsden-Smedley & Catchpole, 1995b) and not in others (Bilgili & Saglam, 2003; Catchpole *et al.*, 1998; Fernandes *et al.*, 2000; Vega *et al.*, 1998). It is important to also define the threshold conditions under which fires will establish and spread in shrub fuels, given their propensity to support fires of extreme intensity under what could be regarded as moderate conditions in forest fuels.

Chapter 3:
Study sites

3.1. Introduction

Field studies were carried out at two sites located in the Canterbury region of the South Island of New Zealand (Figure 3.1). These sites were selected for their proximity to Christchurch and the extensive cover of mature gorse vegetation at each of the sites. Ignition experiments were carried out at a site in the Waimakariri River bed and fuel moisture and fire spread experiments were carried out at a site near the community of Pines Beach. The Waimakariri River site was used for ignition experiments because the patchy nature of the fuels was ideal for conducting numerous small-scale experiments in quick succession. The Pines Beach study site was closer to Christchurch, and therefore minimised travel time for the extended periods of fuel moisture sampling. It had larger and more continuous clumps of gorse fuels suitable for fire spread experiments.

Canterbury is bounded by the Southern Alps mountain range in the west and the coast in the east, with the landscape between these boundaries made up of mountains, basins, hills and extensive plains. The Canterbury Plains extend from the foothills of the mountain ranges in the west to the coast in the east, and represent the largest area of relatively low relief land in New Zealand (Fitzharris *et al.*, 1992). Wide and braided river systems cross the plains from the mountains to the coast. These river systems have formed the plains by depositing large amounts of sediment from the mountain ranges in alluvial fans (Bradshaw & Soons, 2008). Much of the Canterbury Plains has been developed for agriculture, comprising sheep, grain and dairy farming and horticulture. Most of the original natural vegetation has disappeared, with exotic species outnumbering indigenous ones by a ratio of 20:1. A number of significant weed species have become well-established as a result (Meurk, 2008).

The climate across Canterbury is diverse, varying from wet to dry, and strongly influenced by the topography. The Southern Alps exert a major influence on the weather and climate of Canterbury. These mountains form a significant barrier to the predominantly westerly airflow and associated precipitation. There are marked differences in annual rainfall between the West Coast region and Canterbury in the east: Arthurs Pass on the main divide in the west receives an annual average of 4468 mm compared to 630 mm at Christchurch airport (Sturman, 2008). This 'blocking' by the Southern Alps of the westerly airflow produces a foehn effect, commonly known as the 'nor'wester' in Canterbury. This air loses its moisture on the western side of the mountains and descends into Canterbury as a strong, dry and warm wind. The foehn effect also results in frequent dry spells and periods of drought in Canterbury, particularly in mid- to late summer (Ryan, 1987; Sturman, 2008).

The Canterbury Plains (and both of the study sites) fall into climate zone F1 (New Zealand Meteorological Service, 1983). This zone is characterised by low annual rainfall of 500-800 mm, with a slight maximum in the winter. Summers are warm, with temperatures occasionally reaching over 30°C under the influence of foehn winds. Winters are cool with frequent frosts and regular snow. Northeasterly winds prevail, with northwest (foehn) winds occurring more frequently inland.

A network of over 150 weather stations across the country provides information on fire weather and fire danger on a daily basis. An analysis of records from 127 of these fire weather stations ranked Canterbury's climate as the most severe fire climate in New Zealand, followed those of Marlborough and Otago. Six of the top 30 individual weather stations recording the most severe fire climate conditions in New Zealand were located in Canterbury. The two weather stations that were closest to the two study sites, Bottle Lake near Pines Beach and Darfield near the Waimakariri River site, were ranked 37th and was ranked 10th respectively (Pearce *et al.*, 2003).

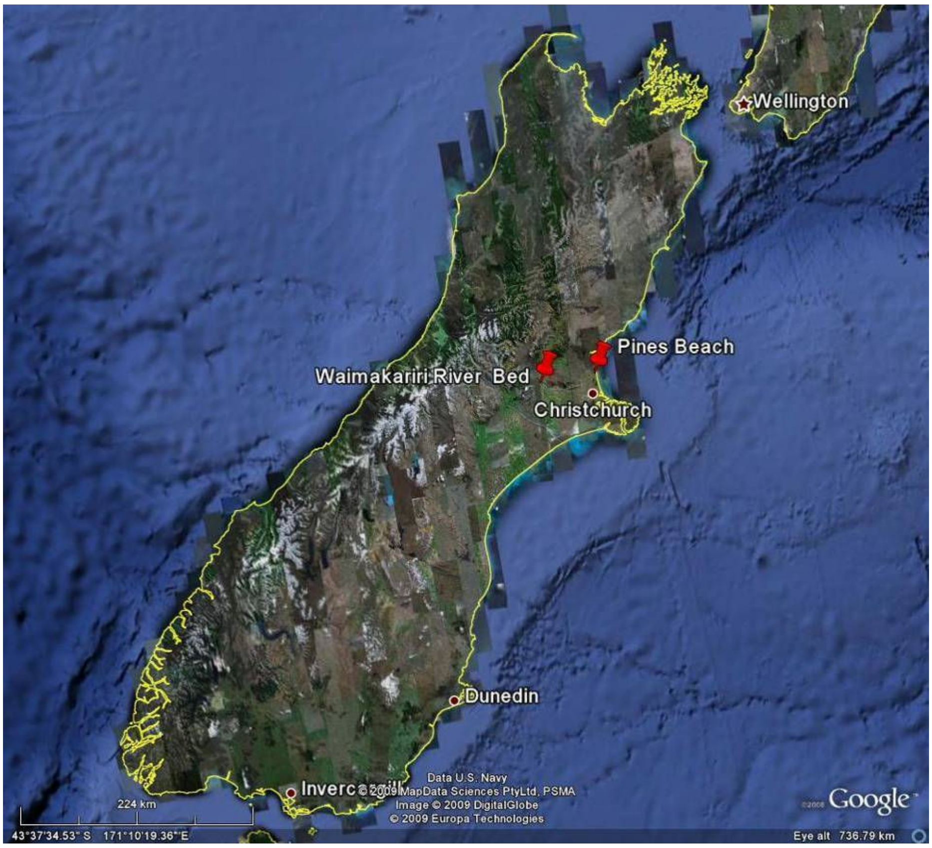

Figure 3.1. A map of the South Island of New Zealand, showing the locations of the Pines Beach and Waimakariri River sites where field studies were conducted. (Source: Google Earth).

3.2. *Waimakariri River site*

Ignition experiments took place at a location in the Waimakariri River bed (43°22′S, 172°04′E), approximately 50 km WNW of Christchurch (Figure 3.2). The elevation at the site was approximately 235 m above sea level. The Waimakariri River has a wide, braided river bed, one of many braided river systems that cross the Canterbury Plains from the Southern Alps mountain ranges in the west to the coastline in the east. The study site was located on a wide part of the river bed, prone only to occasional flooding during very heavy rainfall events. The area contained numerous clumps of gorse bushes scattered across the river bed (Figure 3.3). Being located in a river bed, there was a mostly stony and bouldery cover, underlain by silt-loam sands known as Selwyn-Waimakariri soils (New Zealand Soil Bureau, 1968).

The nearest Remote Automatic Weather Station (RAWS) to this site that was part of the national fire weather monitoring network was Darfield. This was approximately 15 km southeast of the study site. Analyses of 8 years of weather records from this station were undertaken by Pearce *et al.* (2003). The average annual rainfall for the Darfield area was 661 mm, mostly uniformly distributed across the year but with slight peaks in June and July and a minimum in December. The average number of days of 'Very High' and 'Extreme' fire danger recorded at this station for each year of the 8-year period were 30.5 days for forests and 256.6 days for shrub fuels.

Figure 3.2. Location of the Waimakariri River site, west of Christchurch (Source: MapWorld TopoMap NZ, v2.0.61. Scale 1:500,000).

Figure 3.3. The Waimakariri River site, showing scattered clumps of gorse fuels on the stony river bed.

3.3. Pines Beach site

Experiments to determine thresholds for fire spread were carried out near Pines Beach, a small community approximately 20 km north of Christchurch (43°21′S, 172°41′E). The site was located on privately-owned land near the coast (approximately 1.5 km to the east) at sea level (elevation 0 m) and was used predominantly for dairy farming (Figure 3.4). The area was approximately 80 hectares. Vegetation comprised mostly large areas of mature gorse vegetation, ranging from small clumps of a few metres in diameter to large continuous areas, and pasture grasses. Most gorse areas contained mature plants, with average heights ranging from 1.5 m to 2.5 m (Figure 3.5). The land was adjacent to other farmland and a private plantation of *Pinus radiata*. The topography of the area was uniformly flat, with soils described as Yellow-brown Sands, comprising coastal sand and gravel with little or no topsoil differentiation (New Zealand Soil Bureau, 1968).

The nearest Remote Automatic Weather Station (RAWS) to the site that was part of the national fire weather monitoring network was Bottle Lake. This was approximately 12 km south of the study site and the same distance from the coast as the study site. Analysis of 8 years of weather records from this station were undertaken as part of a study of New Zealand's fire climate (Pearce *et al.*, 2003). The average annual rainfall was 520 mm, mostly uniformly distributed across the year but with slight peaks in June and July and minima in December and February. The average number of days of Very High and Extreme fire danger recorded at this station for each year of the 8-year period were 10.9 days for forests and 233.1 days for shrub fuels.

Figure 3.4. Location of the Pines Beach site, north of Christchurch.
(Source: MapWorld TopoMap NZ, v2.0.61. Scale 1:500,000).

Figure 3.5. Gorse fuels at the Pines beach site, showing the patchy nature with surrounding pasture grasses (top) and the vertical structure of the fuels with large amounts of elevated dead fine fuel under the canopy (bottom).

Chapter 4:
Meteorology under the gorse canopy

4.1. Introduction

Weather inputs for fire danger rating and fire behaviour models in New Zealand are collected from a national network of weather stations owned and maintained by different agencies, including the MetService and various Rural Fire Authorities. These weather stations all meet the requirements for FWI System calculations, being specifically located in open clearings and recording temperature (°C), relative humidity (%), 10-minute average wind speed measured at 10 m above the ground (km h^{-1}) and 24-hour rainfall to 12:00 standard time (NZST). Many of these stations also collect hourly weather data, allowing hourly calculation of FWI System outputs. Further information on weather station standards and procedures for weather data collection has been reported by Lawson and Armitage (2008) and Anon (1993).

Accurate models to predict the moisture content of the elevated dead fine fuel layer under the gorse canopy require estimates of meteorological conditions at the fuel level, which can be significantly different to those in an open clearing. Accurate fuel-level meteorological data are therefore important inputs for fuel moisture and fire behaviour models. The objectives of this work were to understand the differences between meteorological conditions at fuel level under the gorse canopy and those in the open at the standard weather station. Exploratory analyses were undertaken that quantified these differences and indicated the main variables affecting fuel level conditions. The applicability of existing models for fuel temperature and relative humidity (Byram & Jemison, 1943; Van Wagner, 1969) to gorse fuels was also evaluated. These analyses are based on limited datasets that were collected incidental to fuel moisture and fire behaviour experiments and comprise only a few days' data in most cases. It is recognised that more extensive data would be required to adequately model meteorological conditions under the gorse canopy. However, these exploratory analyses have indicated the key differences between conditions under the canopy and those in the open, and will be useful for any further research.

4.2. *Methods*

Vegetation at the study site consisted mostly of large areas of mature gorse, ranging from small clumps of a few metres in diameter to large continuous areas, and pasture grasses. Gorse stands contained mature plants, with average heights from 2.0-2.5 m. Stands were uniform, with continuous closed-canopy cover and a layer of elevated dead fine fuels under the canopy down to approximately 0.5 m above ground level. Below this layer there was a near-surface layer, comprising dead gorse needles suspended on stems and branches. There was a continuous layer of surface litter, above a duff layer of needles in various stages of decomposition of around 5 cm depth. Fuel loads were estimated to be from 34.8-39.5 t ha^{-1}, using the fuel load model of Fogarty and Pearce (2000).

A weather station was located at the Pines Beach study site from March 2006 for the duration of the study. This station was erected in an open clearing, within 300 m of the areas from where fuel moisture and under-canopy meteorological measurements were collected and fire experiments carried out (Figure 4.1). The weather station measured: wind speed (Vector Instruments A101M anemometer) and direction (Vector Instruments W200P wind vane) at 10 m above the ground (10-minute average) in km h^{-1}; global solar radiation in W m^{-2} (Apogee PYR-S silicon pyranometer); temperature (°C) and relative humidity (%) approximately 1.5 m above the ground (Vaisala HMP54A humidity and temperature sensor); and rainfall at ground level in increments of 0.2 mm (Hydrological Services TB3-0.2/M tipping bucket rain gauge). Wind speed and direction, solar radiation, temperature and relative humidity were logged at 10 minute intervals, and rainfall at hourly intervals, using a Campbell Scientific CR10X datalogger. Hourly values of the Fire Weather Index (FWI) System were calculated from the weather data, as per Alexander *et al.* (1984). The FWI System calculations were initiated with starting values of FWI System fuel moisture codes from the Bottle Lake permanent fire weather station, located approximately 12 km south of the study site and in the same general location in relation to the coastline. There were occasions when the weather station experienced malfunctions, due to problems with the data logger (battery power) and sensor failure (wiring problems and intense rainfall events that caused saturation and corrosion of connections). In these instances, when they did occur, the missing or erroneous readings were substituted with data from the Bottle Lake weather station. These were isolated events and occurred outside of the periods when fuel moisture measurements or fire experiments were carried out. Data substitution from Bottle Lake is therefore unlikely to have influenced the weather readings used in subsequent analyses.

Figure 4.1. The weather station at the Pines Beach study site.

Intensive (hourly) measurements of elevated dead fine fuel moisture were carried out at Pines Beach on two days – 12 December 2006 and 20 March 2007 (refer to Chapter 5). On each of these occasions, the following additional meteorological measurements were taken from under the canopy (Figure 4.2):

- Wind speed (m s^{-1}) and direction at the surface fuel (litter) level and at 1 m above the ground at 5-second intervals, using sonic anemometers (Gill Instruments Windsonic) with a Unidata Starlogger 6004C datalogger.
- Temperature (°C) and relative humidity (%) at approximately 1 m above ground at 1-minute intervals (Environdata RH21 and TA10 series respectively) with an Environdata Easidata Mark 3 datalogger.

- Temperature (dry and wet bulb) readings collected hourly (in conjunction with collection of fuel moisture samples) using an aspirated psychrometer (Sato SK-RHG No.7450) that was suspended from a tripod at a height of approximately 0.5 m above the ground. These readings were used to determine relative humidity (%).
- Solar radiation (W m^{-2}) at the surface fuel level at 10-minute intervals, using a silicon pyranometer (Apogee PYR-S) and a Campbell 21X datalogger.

During the collection of daily samples of elevated dead fuels (Chapter 5), no weather readings were taken under the canopy.

Figure 4.2. Instrumentation under the gorse canopy during hourly fuel moisture sampling on 12 December 2006. The photograph shows the temperature and relative humidity sensors (rear), pyranometer with datalogger (centre), and sonic anemometer mounted at 1 m above the ground (right foreground). The sonic anemometer at ground level is just visible, off centre to the right of the datalogger.

During the fire spread experiments (Chapter 6), measurements of wind speed were collected in addition to those at 10 m from the standard weather station. These measurements were collected using sonic (Gill Instruments Windsonic) and cup anemometers (Environdata WS30 series) at heights of 1.5 m and 2 m above the ground respectively. These anemometers were located in clearings between gorse clumps and at a suitable distance from the experimental plots so as to avoid any fire-induced effects on the readings.

4.3. Solar radiation

Global solar radiation (W m^{-2}) was measured every 10 minutes at the weather station situated in the open clearing and under the gorse canopy on the surface (litter) layer during the days of hourly fuel moisture sampling (12 December 2006 and 20 March 2007). Further solar radiation measurements were carried out under the canopy during April 2008 to get a better understanding of interception of solar radiation by the canopy and to quantify the amount of radiation received at the level of the elevated dead fuel. Solar radiation was measured on the surface layer and at approximately 1.5 m above ground level (level of the elevated dead fuel) at 10-minute intervals. These measurements were carried out over a period of four days (22-25 April 2008). Early in the morning of each day the sensors were moved to different locations under the canopy. The measurements were carried out using one Apogee PYR-S silicon pyranometer at each height, and a Campbell 21X datalogger.

Analyses of the solar radiation data were carried out with two main objectives:

i. To determine a factor to convert readings of solar radiation in the open to represent the solar radiation received at the level of the elevated dead fuel under the gorse canopy.
ii. To determine a factor to convert readings of solar radiation at the surface layer under the canopy to represent solar radiation received at the level of the elevated dead fuel. This was required to predict the fuel-level temperature and relative humidity using the hourly fuel moisture dataset (Section 4.4).

Conversion factor from solar radiation (open) to 1.5 m canopy level:

Data collected over the four-day period in April 2008 were used. A time-series plot of the measurements under the canopy (Figure 4.3) indicated that only data from two of the four days (23 April and 25 April) were suitable for analysis. The plot of observations from the first day (22 April) showed that the observations at 1.5 m were significantly higher than those at the surface for the entire daylight period. A difference this large was not consistent with readings from any of the other days, and it was suspected that this large difference was because the sensor at 1.5 m was situated in a larger gap that received direct solar radiation (no shading). In addition, measurements only commenced at 14:40 on 22 April and were not collected over a full day, as for the subsequent days. Data from 24 April were also unsuitable, since the observations from the surface sensor were higher than those at 1.5 m for most of the day. This was not consistent with field observations, where there was always a lower level of light at the surface compared to the elevated dead layer. This was most likely from direct sunlight penetrating through an opening onto this sensor. The data from 11:50 to 12:20 on the second day (23 April) were also removed from the dataset, since residual analysis showed that the readings were significantly higher than any of the other surface readings for the two days selected. This was again most likely due to a gap in the canopy that allowed sunlight onto the sensor as the sun moved overhead at this time of the day. These data points were therefore regarded as outliers and excluded from the analysis.

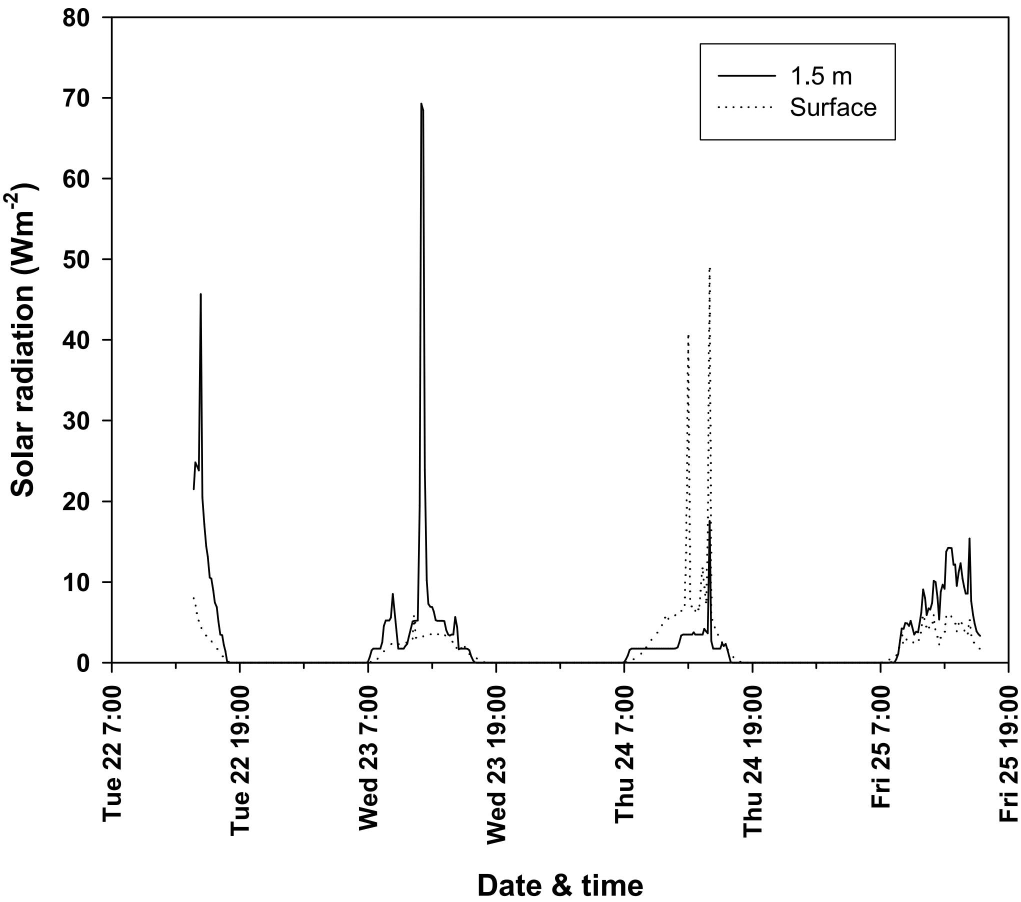

Figure 4.3. Time-series plot of solar radiation measurements collected under the canopy on the surface and at 1.5 m over the period 22-24 April 2008.

Data from the two days were treated as separate datasets, since the sensors were moved to different locations on each day. Data points where observations from both levels (under the canopy and in the open) were zero were removed, to provide some normality to the data (there were a large number of zero observations from overnight periods that skewed the distribution). Conversion factors (the slope coefficient from the regression equations) derived for each day were averaged to provide a single conversion factor. It was also thought likely that there was an issue of repeated measurements because the data were time series, with correlation between the errors in consecutive measurements. To address this, autoregressive models of varying orders were used for the error term to determine the model that provided the best fit to the data. The ARIMA function of the R statistical software programme[9] was used for these and all subsequent autoregressive analyses (R Development Core Team, 2008). A first-order autoregressive model was found to be best in both cases for the error term, to determine solar radiation under the canopy at the level of the elevated fuel (I_c, kW m^{-1}) based on solar radiation received in the open (I_o, kW m^{-1}). For the second day's data (23 April 2008), the fitted model was:

$$(I_c)_t = 0.0115 * (I_o)_t + \eta_t, \tag{4.1}$$

where:

$$\eta_t = 0.6187 * \eta_{t-1} + \varepsilon_t, \tag{4.2}$$

where ε_t was normally distributed with mean 0 and standard deviation 1.2211. Standard errors and p-values associated with the coefficients for equations (4.1) and (4.2) are shown in Table 4.1. A plot of the autocorrelation function with error bars showed that residuals from this model were not serially correlated. The normal quantile plot showed some deviation from normality with an outlier present. The exact cause of this outlier could not be determined, but was most likely due to a short burst of radiation on the sensor under the canopy from either a small gap or from wind opening a small gap to allow this burst. As mentioned earlier, the second day's data had observations removed that were obviously outliers but simulation showed that the effect of removing these data points had a negligible effect on the parameter estimates in the autoregressive model.

Repeating this analysis with the fourth day's data (25 April 2008), the fitted model was:

$$(I_c)_t = 0.0367 * (I_o)_t + \eta_t, \tag{4.3}$$

where:

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9 http://www.r-project.org/

$$\eta_t = 0.8853 * \eta_{t-1} + \varepsilon_t, \qquad (4.4)$$

where ε_t was normally distributed with mean 0 and standard deviation 1.2720. Standard errors and p-values associated with the coefficients for equations (4.3) and (4.4) are shown in Table 4.1. Residual analysis showed no serial correlation, but the normal quantile plot again showed an outlier, most likely due to the reasons mentioned previously.

The average of the two conversion factors from equations (4.1) and (4.3) was 0.0241. The solar radiation received at the level of the elevated dead fuel under the gorse canopy could therefore be estimated as 0.0241 multiplied by the solar radiation received in the open. This means that very little solar radiation penetrated through the gorse canopy to reach the elevated dead fuel (2-3% of the solar radiation in the open).

Plots of observed against predicted values of I_c and residuals for the separate days' data, using equations 4.1 to 4.4 to calculate I_c, are shown in Figure 4.4(a-d). Plots of predicted values of I_c and residuals using the average conversion factor of 0.0241 are shown in Figure 4.4(e, f). In Figure 4.4 and all the similar plots of observed versus predicted values that follow, the solid line represents the line of perfect agreement between observed and predicted, and the dashed line the regression of observed versus predicted values. Comparison of the different conversion factors is shown in Table 4.2. The models to convert I_o to I_c performed reasonably well for the two separate days of data, particularly the model for 23 April 2008 (equation 4.1). However, the combined model (average of conversion factors for equations 4.1 and 4.3) applied to the combined dataset from the two days was less accurate. Further data collection (over longer periods and with greater spatial distribution and more pyranometers) is required to develop a model to adequately predict solar radiation under the gorse canopy using solar radiation in the open.

Beer's Law describes the transmission of radiation through a vegetation canopy, and can be used to calculate the amount of radiation that reaches any given depth under the canopy (Monteith & Unsworth, 1990; Oke, 1978):

$$I_z = I_0 e^{(-kL_z)}, \quad (4.5)$$

where I_z is the amount of solar radiation at depth z under the canopy, k is the attenuation coefficient representing the amount of radiation attenuated by the plant's leaves, and L_z is the Leaf Area Index (LAI) at depth z under the canopy. LAI represents the leaf area cumulated from the top of the canopy to depth z. In this study no measurements of LAI were taken, since the direct measurements of solar radiation were sufficient to provide an indication of the amount of solar radiation reaching the level of the elevated dead fuel. However, to provide an indication of the probable LAI for the gorse stands, equation (4.5) was solved for L_z, since the ratio of solar radiation receipt in the open (I_0) to that in at the level of the elevated dead fuel ($I_{1.5}$) was known (0.0241). The value of k was set at 0.6, which was determined to be broadly representative of shrub or heath vegetation, as described in Pippen (2007). Furthermore, Pippen (2007) explained that the value of k does not vary significantly. Solving equation (4.5) for L_z with $k = 0.6$ provided an LAI value of 6.2. There is very little published information available on LAI or radiation interception for gorse and shrub fuels in general. However, this value does seem to fit well with published values for forests with closed canopies (Breuer *et al.*, 2003; Jonckheere *et al.*, 2004).

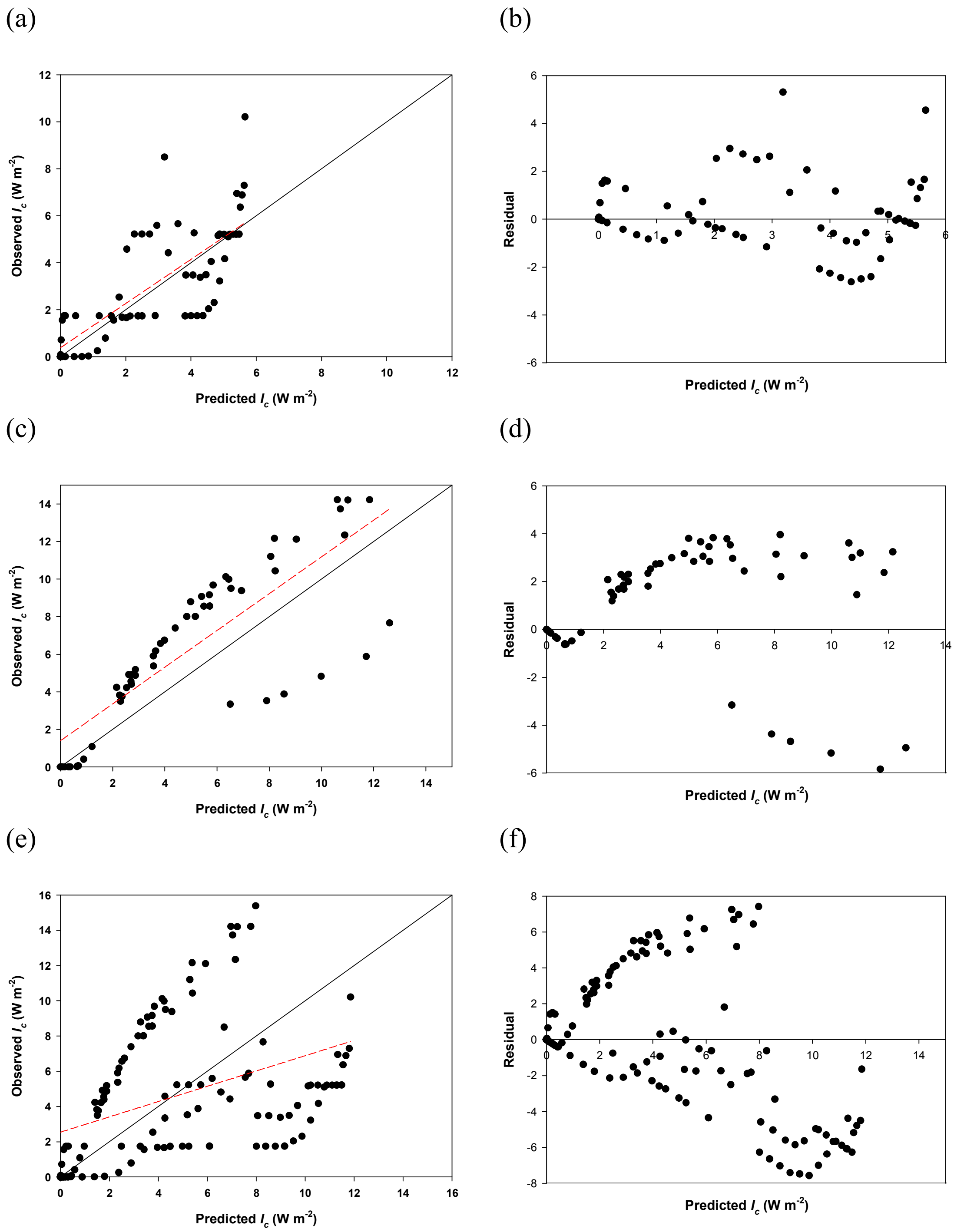


Figure 4.4. Plots of observed against predicted values of I_c and residuals using: equations (4.1) and (4.2) for 23 April 2008 (a, b); equations (4.3) and (4.4) for 25 April 2008 (c, d); and the average conversion factor of 0.024 for both days (e, f). Note that patterns in the residuals are due to correlations in the error term. In this and all the similar plots that follow, the solid line represents the line of perfect agreement between observed and predicted, and the dashed line the regression of observed versus predicted values.

Table 4.1. Standard errors and p-values associated with the coefficients for each of the regression equations developed to predict I_c.

Equation	Date	Variable	Coefficient	Standard error	p-value
4.2	23 Apr 08	*ar1*	0.6187	0.0974	<0.0001
4.1		I_o	0.0115	0.0013	<0.0001
4.4	25 Apr 08	*ar1*	0.8853	0.0595	<0.0001
4.3		I_o	0.0367	0.0040	<0.0001

Table 4.2. Comparison of equations for conversion of solar radiation readings in the open to reflect solar radiation receipt at the level of the elevated dead fuel under the canopy (approximately 1.5 m above the ground).

Date	23 April 2008	25 April 2008	Combined
Conversion factor	0.0115	0.0367	0.0241
(& equation)	(4.1)	(4.3)	(ave 4.1 & 4.3)
N	64	56	120
R^2	0.58	0.67	0.17
ME	0.21	1.29	-0.15
RMSE	1.56	2.79	4.05

Conversion of solar radiation at surface level to 1.5 m under the canopy:
The same datasets were used for this analysis to convert solar radiation measured at the surface level to that received at 1.5 m under the canopy (representing the level of the elevated dead fuel). The two days' data were again treated separately, with data points where both observations were 0 removed. Conversion factors derived for each day were averaged to produce a single factor. A first-order autoregressive model was used for the error term to determine solar radiation under the canopy at the level of the elevated fuel (I_c) using solar radiation received at the surface level under the gorse canopy (I_s). For the second day's data (23 April 2008), the model was:

$$(I_c)_t = 1.3707 * (I_s)_t + \eta_t, \tag{4.6}$$

where:

$$\eta_t = 0.5682 * \eta_{t-1} + \varepsilon_t, \tag{4.7}$$

with ε_t normally distributed with mean 0 and standard deviation 1.3015. Standard errors and p-values associated with the coefficients for equations (4.6) and (4.7) are shown in Table 4.3. A plot of the autocorrelation function showed that residuals from this model were not serially correlated. The normal quantile plot showed slight deviation from normality with possible outliers. The reason for these outliers was again likely due to small gaps or variations in the density of the canopy and exposure of the sensors to short bursts of radiation during the day.

For the fourth day's data (25 April 2008) the model was:

$$(I_c)_t = 1.9606 * (I_s)_t + \eta_t, \tag{4.8}$$

where:

$$\eta_t = 0.7816 * \eta_{t-1} + \varepsilon_t, \tag{4.9}$$

with ε_t normally distributed with mean 0 and standard deviation 1.0488. Standard errors and p-values associated with the coefficients for equations (4.8) and (4.9) are shown in Table 4.3. Again, the plot of the autocorrelation function showed that model residuals were not serially correlated, but the normal quantile plot showed deviation from normality with possible outliers for the same reasons as discussed previously.

The average of the two conversion factors from equations (4.6) and (4.8) was 1.6657. Solar radiation received at the level of the elevated dead fuel under the gorse canopy could be estimated as the solar radiation received at the surface level under the canopy multiplied by 1.6657.

Plots of observed against predicted values of I_c and residuals for the separate days' data, using equations (4.6) to (4.9) to calculate I_c, are shown in Figure 4.5(a-d). The plots of predicted values of I_c and residuals using the average conversion factor of 1.6657 are shown in Figure 4.5(e, f). Comparison of the different conversion factors is shown in Table 4.4. The models to convert I_s to I_c performed reasonably well for the two separate days of data. The combined model (average of conversion factors for equations (4.6) and (4.8)) applied to the combined dataset from the two days also performed reasonably well. This conversion factor, derived from the average of the two day's models, was then applied to the dataset of hourly fuel moisture sampling to determine I_c for the fuel-level temperature modelling (Section 4.4).

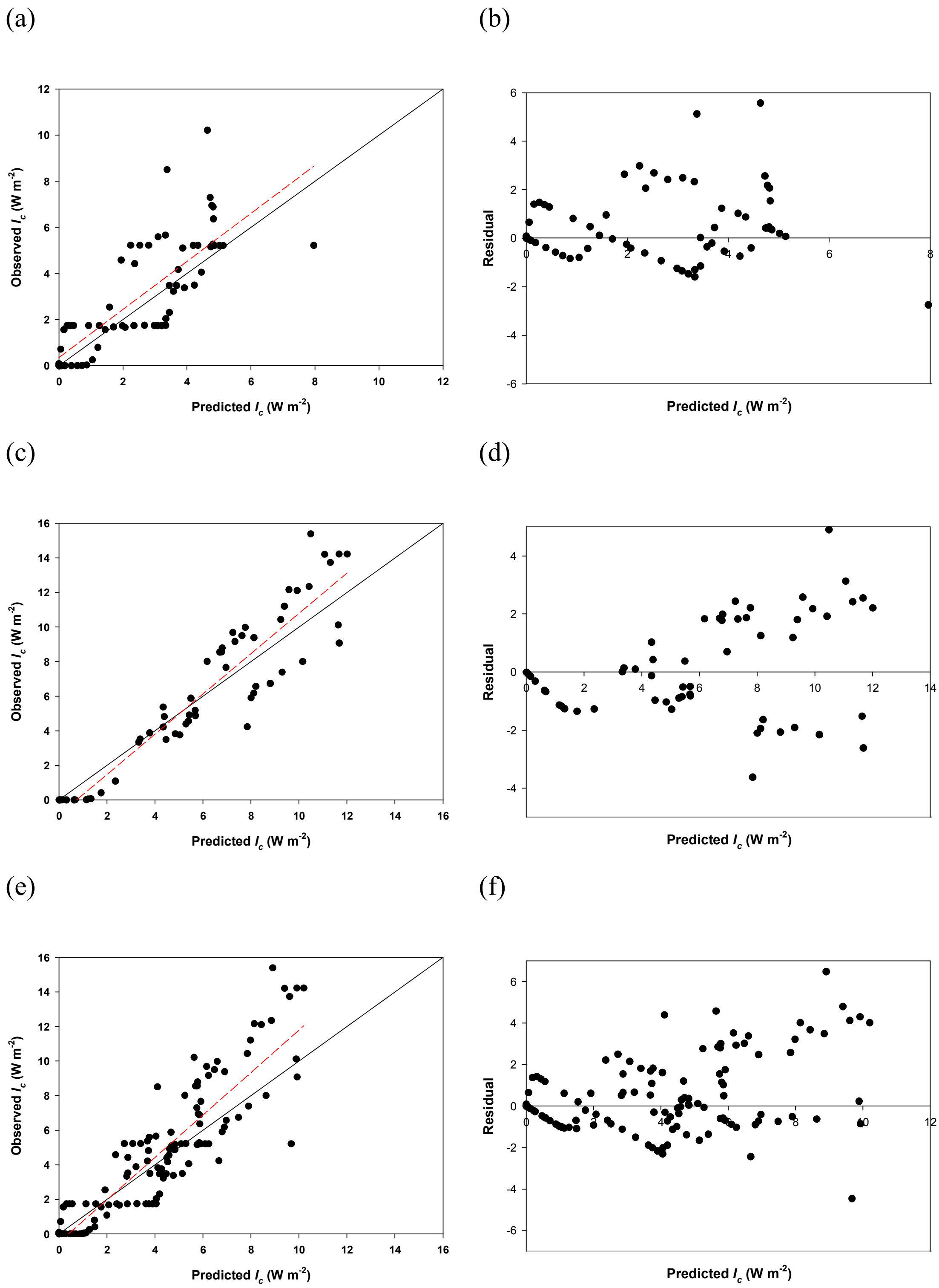


Figure 4.5. Plots of observed against predicted values of I_c and residuals using: equations (4.5) and (4.6) for 23 April 2008 (a, b); equations (4.7) and (4.8) for 25 April 2008 (c, d); and the average conversion factor of 1.6657 for both days (e, f). Note that patterns in the residuals are due to correlations in the error term.

Table 4.3. Standard errors and p-values associated with the coefficients for each of the regression equations developed to predict I_c.

Equation	Date	Variable	Coefficient	Standard error	p-value
4.7	23 Apr 08	*ar1*	0.5682	0.1375	<0.0001
4.6		I_s	1.3707	0.2035	<0.0001
4.9	25 Apr 08	*ar1*	0.7816	0.0848	<0.0001
4.8		I_s	1.9606	0.1359	<0.0001

Table 4.4. Comparison of equations for conversion of solar radiation readings at surface level under the gorse canopy to reflect solar radiation receipt at the level of the elevated dead fuel.

Date	23 April 2008	25 April 2008	Combined
Conversion factor	1.3707	1.9606	1.6657
(& equation)	(4.6)	(4.8)	(ave 4.6 & 4.8)
N	64	56	120
R^2	0.60	0.86	0.79
ME	0.46	0.16	0.46
RMSE	1.58	1.73	1.90

4.4. Fuel temperature and relative humidity

Relative humidity is an important variable that controls the equilibrium moisture content (EMC) of a fuel particle. Temperature is also important, but to a lesser extent than relative humidity. These variables should be measured at the fuel surface to accurately model changes in moisture (Viney, 1991). However, it is difficult to accurately measure temperature and relative humidity at the surface of small dead gorse needles. Measurements of temperature and relative humidity taken under the canopy at a height of 1 m during field studies were therefore assumed to represent fuel-level conditions. This assumption was also based on the fact that little solar radiation penetrates the canopy to heat the gorse needles above ambient temperature (refer to Section 4.3).

4.4.1. Byram and Jemison (1943)

Byram and Jemison (1943) developed models to predict fuel temperature and relative humidity for surface fuels on the forest floor, based on the heating effects of solar radiation. Predictions from these models were compared with temperature and relative humidity measurements collected under the canopy at the level of the elevated dead fuel during the hourly fuel sampling on 12 December 2006 and 20 March 2007.

Fuel-level temperature

Viney (1991) determined a metric form of Byram and Jemison's (1943) model for fuel temperature (T_f, in °C):

$$T_f = T_a + \frac{I}{42.5u + 32.7}, \qquad (4.10)$$

where T_a is the air temperature (°C), I is solar radiation (W m^{-2}) and u is wind speed (m s^{-1}). For this study, T_f was calculated using T_a measured in the open and u measured under the canopy at a height of approximately 1 m. Solar radiation (I) received at the level of the elevated fuel was estimated from the solar radiation measured at the ground (surface) level under the canopy using a conversion factor of

1.6657, derived from field data (refer to Section 4.3). The plot of actual fuel-level temperature against that predicted using equation (4.10) (Figure 4.6) shows that Byram and Jemison's model did not predict fuel-level temperature well ($R^2 = 0.73$ (of the regression of observed versus predicted fuel-level temperature), ME = -2.28, RMSE = 4.23, $n = 125$), in most cases significantly overpredicting T_f.

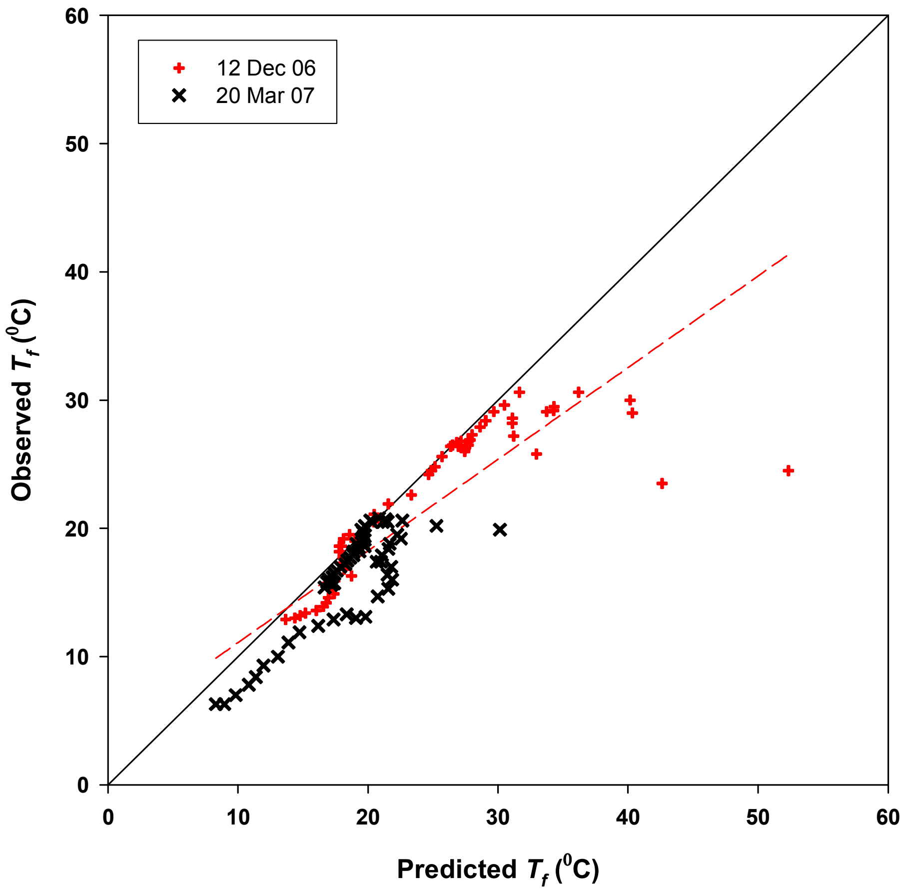


Figure 4.6. Observed fuel-level temperature (T_f) against that predicted, calculated using Byram and Jemison's (1943) equation converted to metric form (Viney, 1991).

Fuel-level relative humidity

Viney (1991) also determined a metric form of Byram and Jemison's (1943) equation for fuel-level relative humidity (H_f, in %):

$$H_f = H_a e^{0.059(T_a - T_f)}, \tag{4.11}$$

where H_a is relative humidity of the air (%) and T_f and T_a are as previously defined. H_f was calculated using equation (4.11), with relative humidity (H_a) and temperature (T_a) measured in the open at the onsite weather station, and T_f measured under the canopy at fuel level. The plot of observed H_f against that predicted (Figure 4.7) shows that the model predicted H_f poorly (R^2 = 0.87, ME = 7.49, RMSE = 12.20, n = 125), with significant underprediction. This was particularly the case for 20 March 2007.

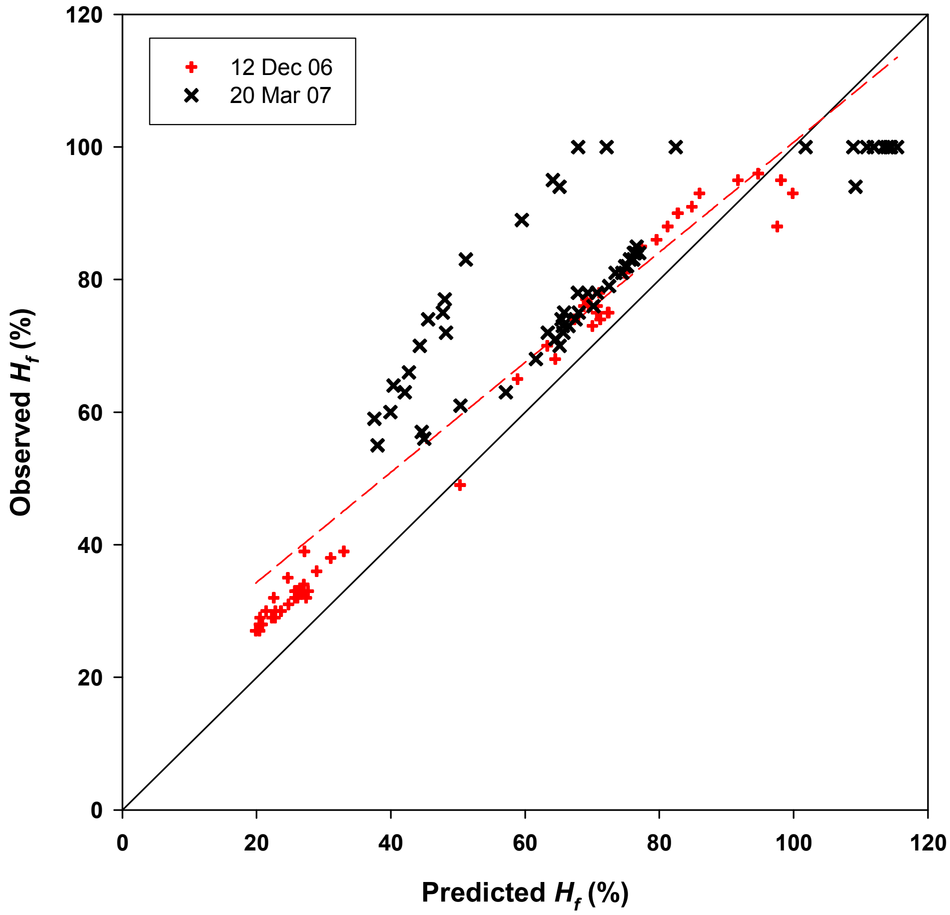


Figure 4.7. Observed fuel-level relative humidity (H_f) against that predicted, calculated using Byram and Jemison's (1943) equation converted to metric form (Viney, 1991).

4.4.2. Van Wagner (1969)

Van Wagner (1969) developed a relationship to predict the surface temperature of forest litter (T_f) based on T_a, the heating effect of solar radiation (I, W m^{-2}) and wind speed under the canopy (u_f, m s^{-1}):

$$T_f = T_a + aIe^{-0.224u_f}, \tag{4.12}$$

where a is a constant based on the litter type. Van Wagner experimentally derived values for a of 0.035 for jack pine (*Pinus banksiana*) and 0.028 for trembling aspen (*Populus tremuloides*) litter (Viney, 1991).

Equation (4.12) was applied to the data collected under the canopy at the level of the elevated dead fuel during the hourly fuel sampling on 12 December 2006 and 20 March 2007. A least squares approach was used to determine the value of a that minimised the sum of squares of error (SSE) between the observed and predicted values of T_f. The SSE was minimised using the 'Solver' application in Microsoft Excel® and equation (4.12) was initiated using the value of 0.028 from Van Wagner (1969), as in Viney (1991). The value of a that minimised the SSE was found to be 0.0009. The plot of actual fuel-level temperature against that predicted (Figure 4.8) using equation (4.12) with a = 0.0009 shows reasonably weak predictions of T_f (R^2 = 0.92, ME = -0.74, RMSE = 1.89, n = 125), but better than those from Byram and Jemison (1943). The low value of a (0.0009) means that T_f is largely predicted from T_a. Underprediction of T_f is evident, again particularly for the data from 20 March 2007.

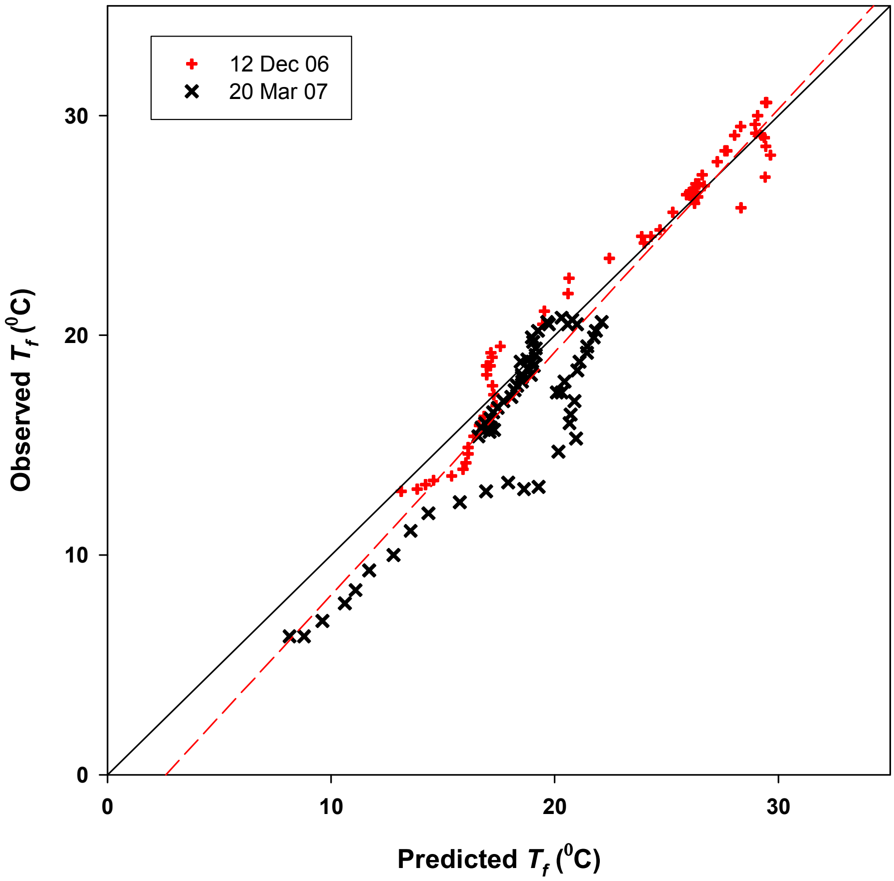


Figure 4.8. Observed fuel-level relative temperature (T_f) against that predicted, calculated using Van Wagner's (1969) equation with fitted constant.

4.4.3. Lag modelling

Attempts were made to model T_f and H_f using a time lag approach and the weather data from the hourly fuel moisture sampling. This was based similar theory to that of the model of Catchpole *et al.* (2001), which was developed to predict fuel moisture content based on the response time of the fuel. A detailed description of this model is contained in Section 5.2.3. The model is based on a first-order differential equation that determines the response time of the fuel. In this case the equation was used to determine the response time for temperature or relative humidity, i.e. the time lag for the temperature or relative humidity at fuel level to respond to changes in the air temperature or relative humidity in the open. If the response time (τ) is known, then T_f (or H_f) for the current hour (t) can be modelled using the values of T_a or H_a in the open for both the current (t) and previous hour (t-1) and T_f (or H_f) at time t-1.

Fuel-level temperature

The equation to predict fuel-level temperature $(T_f)_t$ at time t was:

$$\left(T_f\right)_t = \lambda^2\left(T_f\right)_{t-1} + \lambda(1-\lambda)\left(T_a\right)_{t-1} + (1-\lambda)\left(T_a\right)_t , \qquad (4.13)$$

where $\lambda = \exp\left(-1/(2\tau)\right)$.

The response time (τ) was modelled from solar radiation (I, W m^{-2}) and wind speed (u, m s^{-1}) under the canopy (at fuel level) as:

$$\tau = a + b * I + c * u , \qquad (4.14)$$

where a, b and c are constants. The constants were derived from the field data by using equation (4.13) to find the values that minimised the sum of squares of error (SSE) between the predicted and observed values of T_f. This was carried out using the 'Solver' application in Microsoft Excel®, and produced values of 1.390 (a), 0.0009 (b) and -0.740 (c). The average value of τ was 1.12 (range 0.76-2.51).

Figure 4.9 shows the time-series plot of actual fuel-level temperature ($T_{f\text{-}act}$), air temperature measured in the open (T_a) and predicted fuel-level temperature (T_f and T_{f2}) using two approaches. The first approach (T_f) used the previous hour's *actual* fuel-level temperature as input into equation (4.13) to predict the current hour's fuel-level temperature. The second approach (T_{f2}) used the previous hour's *predicted* fuel-level temperature (from equation 4.13) to predict the current hour's fuel-level temperature, with values of a, b and c fixed at those derived above. It was used to simulate the bookkeeping procedure that would be applied in practice.

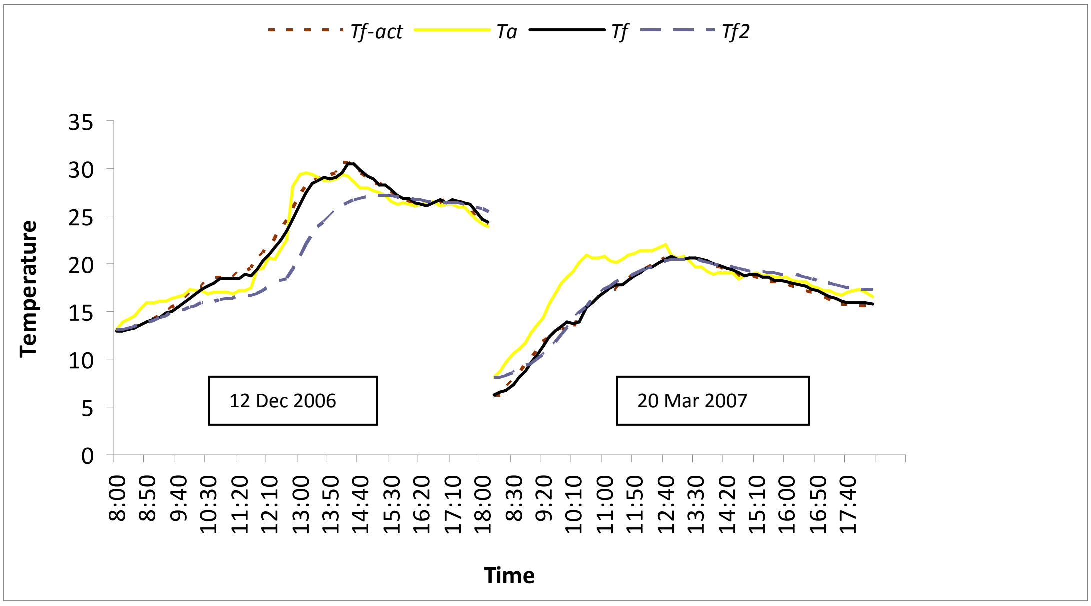


Figure 4.9. Time-series plots for 12 December 2006 (left) and 20 March 2007 (right) of predicted fuel-level temperature using the two approaches described (T_f and T_{f2}), measured fuel-level temperature ($T_{f\text{-}act}$) and air temperature in the open (T_a).

The first approach (T_f), using the previous hour's *actual* fuel-level temperature, followed the observed fuel-level temperature very well and provided a good fit (R^2 = 0.99, ME = 0.06, RMSE = 0.42), as evident in Figures 4.9 and 4.10(a). The second approach (T_{f2}), using the previous hour's *predicted* fuel-level temperature, did not follow the observed fuel-level temperature as well (Figures 4.9 and 4.10b), with a difference of up to 6.5°C evident during the period from 09:30 to 15:30 on 12 December 2006 (R^2 = 0.86, ME = 0.65, RMSE = 2.12).

(a) (b)

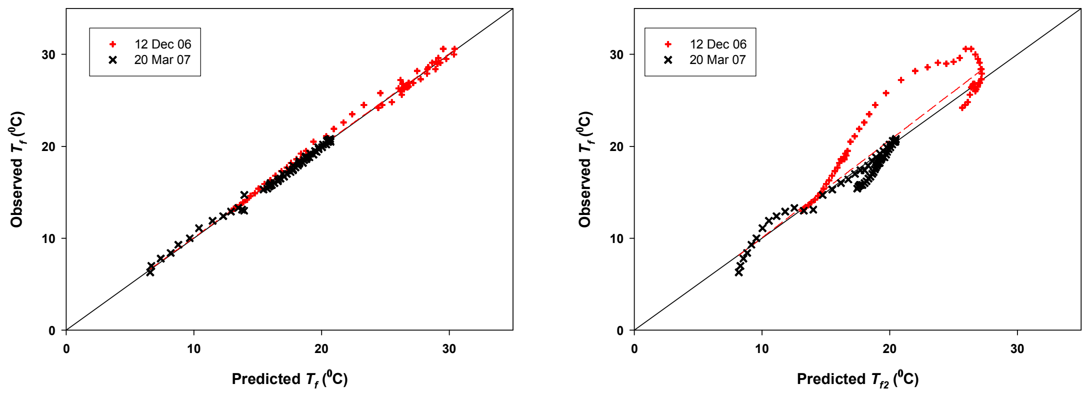


Figure 4.10. Observed fuel-level temperature ($T_{f\text{-}act}$) against predicted, calculated using the two approaches described: T_f (a) and T_{f2} (b).

Fuel-level relative humidity

The equation to predict fuel-level relative humidity $(H_f)_t$ at time t was:

$$\left(H_f\right)_t = \lambda^2\left(H_f\right)_{t-1} + \lambda(1-\lambda)\left(H_a\right)_{t-1} + (1-\lambda)\left(H_a\right)_t \qquad (4.15)$$

The response time (τ) was modelled as a linear function of the difference between the air temperature in the open (T_a) and that recorded at fuel level (T_f). This was consistent with the approach of Byram and Jemison (1943), and was found to be a more suitable approach than using T_a and T_f separately. The equation for τ was:

$$\tau = a + b * (T_a - T_f) \qquad (4.16)$$

Solving using equation (4.15) and minimising the SSE provided values of 2.082 (a) and 0.097 (b). The average value of τ was 2.15 (range 1.88-2.68).

The time-series plot of actual fuel-level relative humidity ($H_{f\text{-}act}$), relative humidity measured in the open (H_a) and predicted fuel-level relative humidity using the same two approaches (H_f and H_{f2}) are shown in Figure 4.11.

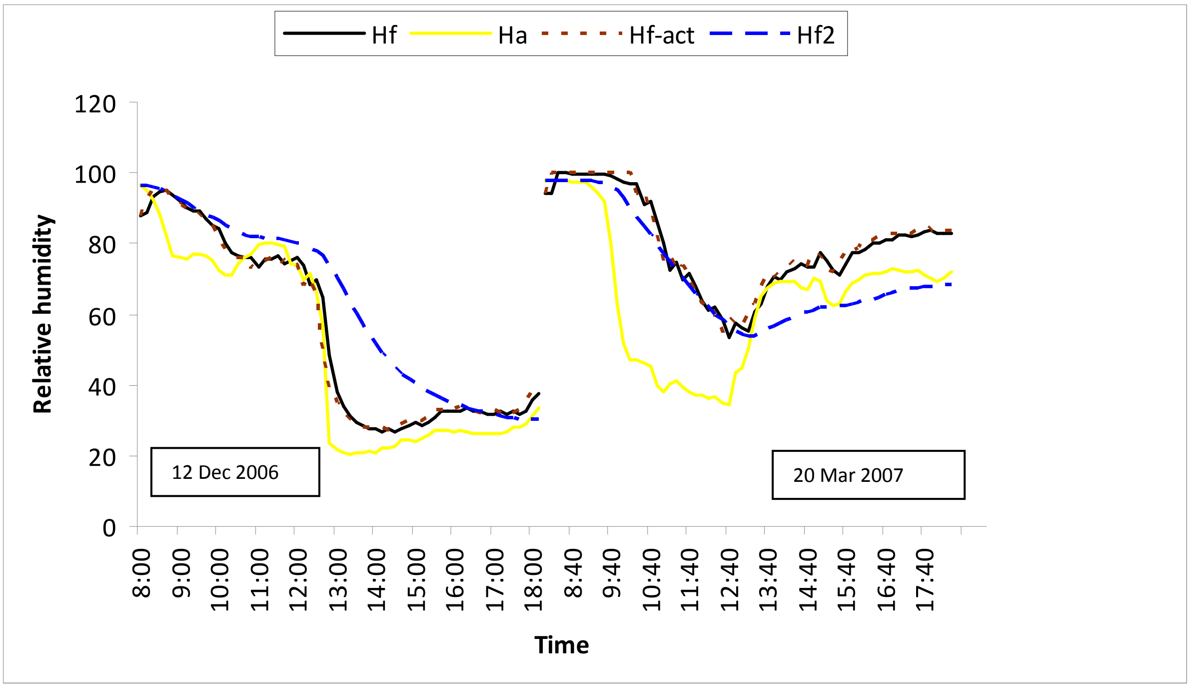


Figure 4.11. Time-series plots for 12 December 2006 (left) and 20 March 2007 (right) of predicted fuel-level relative humidity using the two approaches described (H_f and H_{f2}), measured fuel-level relative humidity ($H_{f\text{-}act}$) and relative humidity in the open (H_a).

The first approach (H_f), using the previous hour's *actual* fuel-level relative humidity to calculate the current hour's fuel-level relative humidity, followed the observed fuel-level relative humidity well and provided a good fit to the data (R^2 = 0.99, ME = 0.28, RMSE = 2.73), as shown in Figures 4.11 and 4.12(a). The second approach (H_{f2}), using the previous hour's *predicted* fuel-level relative humidity, did not follow the observed fuel-level relative humidity very well (Figures 4.11 and 4.12b) (R^2 = 0.73, ME = 0.40, RMSE = 12.48). This was particularly evident during the afternoon periods of both days, and most noticeably on 12 December 2006. This was most likely due to complex micrometeorological and physiological processes taking place under the canopy (refer to Section 4.4.5).

(a) (b)

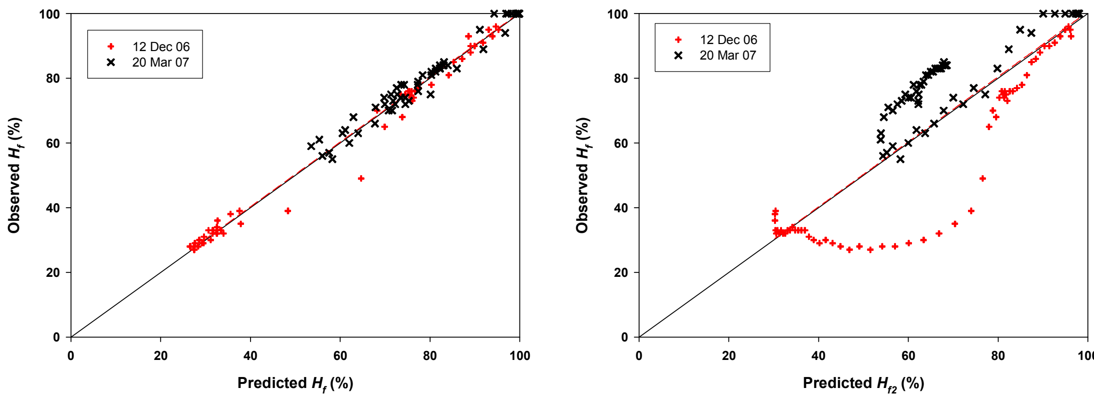


Figure 4.12. Observed fuel-level relative humidity ($H_{f\text{-}act}$) against predicted, calculated using the two approaches described: H_f (a) and H_{f2} (b).

4.4.4. Regression modelling

The models of Byram and Jemison (1943) and the bookkeeping time-lag approach predicted fuel-level temperature and relative humidity poorly. Linear regression models were therefore developed to predict T_f and H_f. Regression models developed from only two days of field data would not be adequate to provide predictive models suitable for broad landscape-scale application under a range of meteorological conditions. However, regression models could provide an indication of the key weather variables influencing temperature and relative humidity at fuel level under the canopy, and provide direction for further research.

Fuel-level temperature

Observations of temperature both under the canopy at fuel-level and in the open were collected at consecutive 10-minute intervals throughout each of the two hourly fuel moisture sampling days, 12 December 2006 and 20 March 2007. The two day's data were treated as separate datasets, since the weather conditions were quite different on the two days (refer Section 4.4.5). It was also likely that there was an issue of repeated measurements because the data were time series, with correlation between the errors in consecutive measurements of temperature. To address this, autoregressive models of varying orders were again used for the error term to determine the model that provided the best fit to the data. All key variables were initially included in regression modelling to determine their significance – temperature and relative humidity in the open, and solar radiation and wind speed at fuel level. For the first dataset (12 December 2006), the best model to predict fuel-level temperature (T_f) used air temperature in the open (T_a), solar radiation at the level of the elevated dead fuel (I) and an AR(2) model for the error term:

$$(T_f)_t = (T_a)_t + 0.0017 * (I)_t + \eta_t, \qquad (4.17)$$

where:

$$\eta_t = 1.1170 * \eta_{t-1} - 0.2575 * \eta_{t-2} + \varepsilon_t, \qquad (4.18)$$

with ε_t normally distributed with mean 0 and standard deviation 0.4807. Fixing the intercept at 0 and the coefficient for T_a at 1, as in equation (4.17), did not give a significantly worse model than the model given by allowing these coefficients to vary. This aligned well with the form of the model of Byram and Jemison (1943), as shown in equation (4.10). Standard errors and p-values associated with the coefficients for equations (4.17) and (4.18) are shown in Table 4.5. A plot of the autocorrelation function with error bars showed that residuals from this model were not serially correlated. The normal quantile plot showed little deviation from normality, with minimal evidence of outliers. Plots of observed against predicted values of T_f, using equation (4.17) with the error term set to its mean value of zero, and residuals are shown in Figure 4.13(a, b). This model mostly predicted T_f well, with some slight overprediction evident (R^2 = 0.96, ME = 0.08, RMSE = 1.11).

For the second day's data (20 March 2007), the most appropriate model was again based on T_a and I and an AR(2) model for the error term. In this case an intercept term was included in the model, since it was close to significant and provided a markedly better fit to the data compared to the model with an intercept of 0:

$$(T_f)_t = -1.6887 + (T_a)_t + 0.0008 * (I)_t + \eta_t, \qquad (4.19)$$

where:

$$\eta_t = 1.2873 * \eta_{t-1} - 0.3283 * \eta_{t-2} + \varepsilon_t \,, \tag{4.20}$$

with ε_t normally distributed with mean 0 and standard deviation 0.3709. Standard errors and p-values associated with the coefficients for equations (4.19) and (4.20) are shown in Table 4.5. The coefficient for I was not significant for equation (4.19), with $p = 0.28$. However, the form of this equation was retained to maintain consistency with equation (4.17) for 12 December 2006. The plot of the autocorrelation function showed no evidence of serial correlation of residuals from the model, and the normal quantile plot again showed little deviation from normality. The plots of observed against predicted values of T_f from equation (4.19) and residuals are shown in Figure 4.13(c, d). This model did not fit the data as well as the model for 12 December 2006, with both over- and underprediction of T_f apparent ($R^2 = 0.76$, ME = 0.02, RMSE = 1.75).

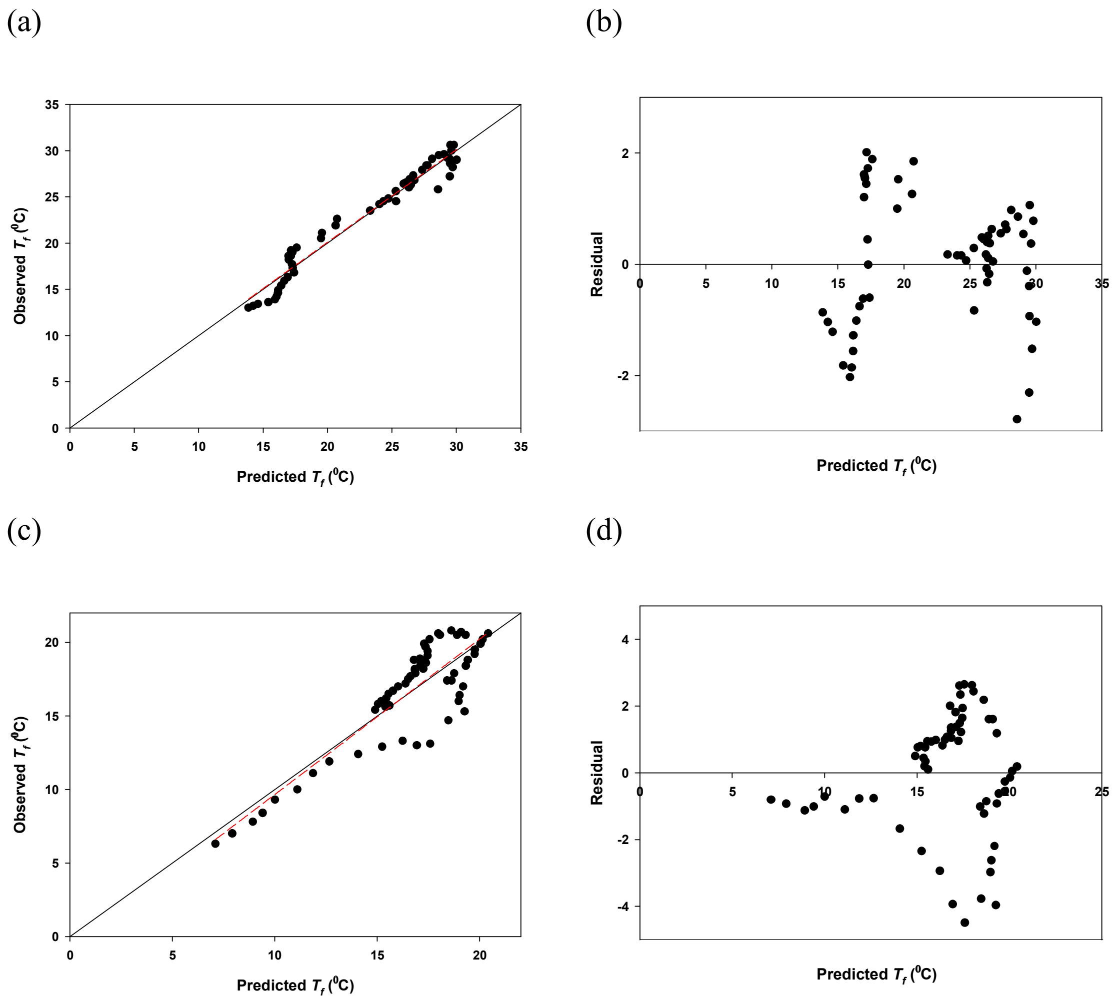


Figure 4.13. Plots of observed against predicted values of T_f and residuals using the regression equations (4.17) and (4.18) for 12 December 2006 (a, b), and equations (4.19) and (4.20) for 20 March 2007 (c, d). Note that patterns in the residuals are due to the correlations in the error term.

Table 4.5. Standard errors and *p*-values associated with the coefficients for each of the regression equations developed to predict T_f.

Equation	Date	Variable	Coefficient	Standard error	*p*-value
4.18	12 Dec 06	*ar1*	1.1170	0.1232	<0.0001
		ar2	-0.2575	0.1242	0.04
4.17		*I*	0.0017	0.0003	<0.0001
4.20	20 Mar 07	*ar1*	1.2873	0.1183	<0.0001
		ar2	-0.3283	0.1185	0.006
4.19		*Intercept*	-1.6887	0.9404	0.07
		I	0.0008	0.0007	0.28

Fuel-level relative humidity

Observations of relative humidity at fuel level under the canopy and in the open were collected as described previously for temperature. The same regression procedures were followed, using autoregressive models for the error term. For the first dataset (12 December 2006), the most appropriate model was based on an AR(1) model for the error term:

$$\ln\left(\frac{H_f}{H_a}\right)_t = 0.1242 * (T_a - T_f)_t + \eta_t, \qquad (4.21)$$

where:

$$\eta_t = 0.9792 * \eta_{t-1} + \varepsilon_t, \qquad (4.22)$$

where ε_t was normally distributed with mean 0 and standard deviation 0.0402. Standard errors and *p*-values associated with the coefficients for equations (4.21) and (4.22) are shown in Table 4.6. The plot of the autocorrelation function showed no evidence of serial correlation of residuals from the model, and the normal quantile plot showed little deviation from normality. This model was also of the same form as that developed by Byram and Jemison (1943) to predict H_f (equation 4.11). The plots of observed against predicted values of H_f, using equation (4.21) with the error term set to its mean value of zero, and residuals are shown in Figure 4.14(a, b). This model predicted H_f reasonably well, but tended to overpredict ($R^2 = 0.97$, ME = 6.39, RMSE = 8.47). A further problem was that, in four instances, H_f was predicted to be greater than 100% (H_a was above 93% in these instances).

The model derived for the second day's data (20 March 2007) was of the same form as for the model for 12 December 2006 (equation 4.21), with an AR(1) model for the error term:

$$\ln\left(\frac{H_f}{H_a}\right)_t = 0.1120 * (T_a - T_f)_t + \eta_t, \qquad (4.23)$$

where:

$$\eta_t = 0.9661 * \eta_{t-1} + \varepsilon_t, \qquad (4.24)$$

where ε_t was normally distributed with mean 0 and standard deviation 0.0486. Standard errors and p-values associated with the coefficients for equations (4.23) and (4.24) are shown in Table 4.6. The plot of the autocorrelation function again showed no evidence of serial correlation of residuals from the model, and the normal quantile plot showed little deviation from normality. The plots of observed against predicted values of H_f, from equation (4.23), and residuals are shown in Figure 4.14(c, d). This model predicted H_f poorly compared to the model for 12 December 2006, and mostly overpredicted H_f ($R^2 = 0.86$, ME = 2.57, RMSE = 15.40). There were also a number of instances where predicted H_f was significantly higher than 100% (up to 134%). In all of these cases, H_a was 100%.

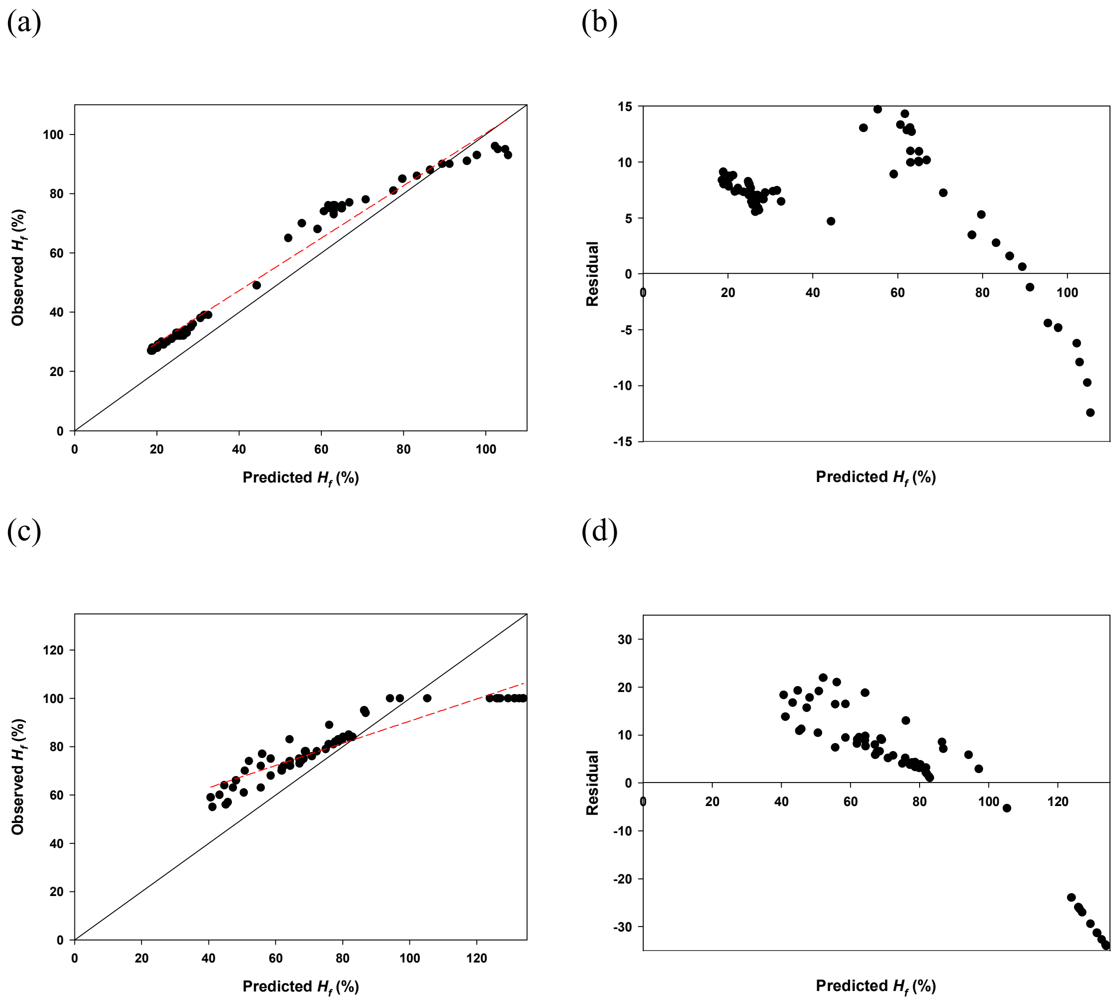


Figure 4.14. Plots of observed against predicted values of H_f and residuals using the regression equations (4.21) and (4.22) for 12 December 2006 (a, b), and equations (4.23) and (4.24) for 20 March 2007 (c, d). Note that patterns in the residuals are due to the correlations in the error term.

Table 4.6. Standard errors and p-values associated with the coefficients for each of the regression equations developed to predict H_f.

Equation	Date	Variable	Coefficient	Standard error	*p*-value
4.22	12 Dec 06	*ar1*	0.9792	0.0182	<0.0001
4.21		$(T_a\text{-}T_f)$	0.1242	0.0081	<0.0001
4.24	20 Mar 07	*ar1*	0.9661	0.0272	<0.0001
4.23		$(T_a\text{-}T_f)$	0.1120	0.0153	<0.0001

Many of the problems encountered in modelling H_f (and T_f) were most likely due to complex micrometeorological processes taking place under the canopy such as trapping of heat and moisture, and physiological processes such as transpiration (refer Section 4.4.5). With these very small datasets collected over only two days, developing models that were any more reliable than those presented was not feasible.

4.4.5. Summary

It was not possible to develop reliable predictive models of fuel-level temperature and relative humidity under the gorse canopy using meteorological observations from the weather station in the open. Byram and Jemison's models (1943) did not predict fuel-level temperature or relative humidity well. Van Wagner's (1969) fuel temperature model with minimal radiation input performed slightly better. This is most likely due to the fact that these models account for heating of fuels by solar radiation. Under the gorse canopy very little direct solar radiation penetrated the canopy and reached the elevated dead gorse fuels (refer to Section 4.3). An additional reason could be that fuel temperature (of the elevated dead gorse needles) was not directly measured – the air temperature at fuel level was taken to represent fuel temperature. Of course, accurately determining the temperature of the very small gorse needles in the field with thermocouples would be very difficult, but it is possible that further error was introduced in assuming that the air temperature at fuel level represented the actual fuel temperature. The other two approaches, based on incorporating a time-lag effect and developing linear regression models from the field data, provided some encouraging results but still did not produce reliable predictive models. Using datasets that represented only two days of measurements in the field was a major limitation. The relationships that were determined could not be reliably extended across all types of weather conditions and gorse fuel complexes, beyond the conditions under which the data were collected. There are also likely to be problems in modelling fuel-level temperature and relative humidity because more complex physiological and micrometeorological processes within the gorse canopy were not measured and not accounted for. This is evident by examining the time-series plots of temperature and relative humidity recorded in the open and at fuel-level under the gorse canopy for the two days (Figures 4.15 and 4.16).

(a) (b)

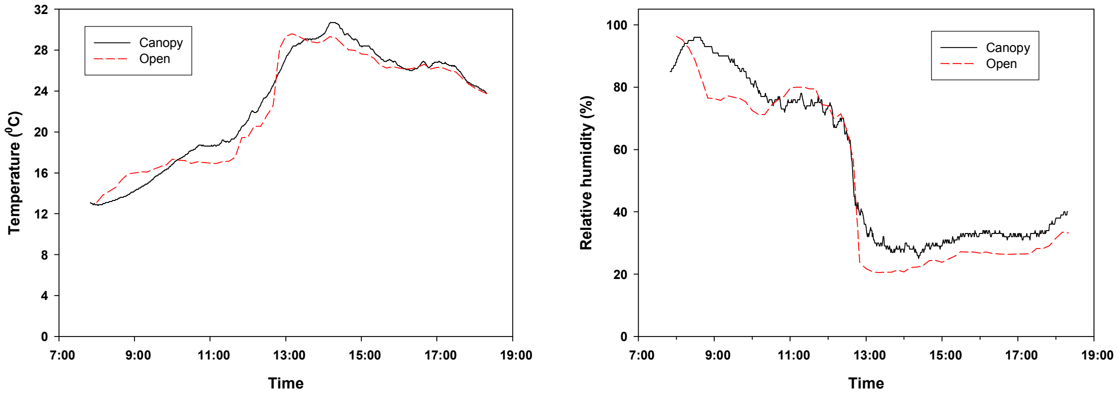


Figure 4.15. Time-series plots of temperature (a) and relative humidity (b) recorded in the open and under the canopy at fuel level for the hourly sampling carried out on 12 December 2006.

(a) (b)

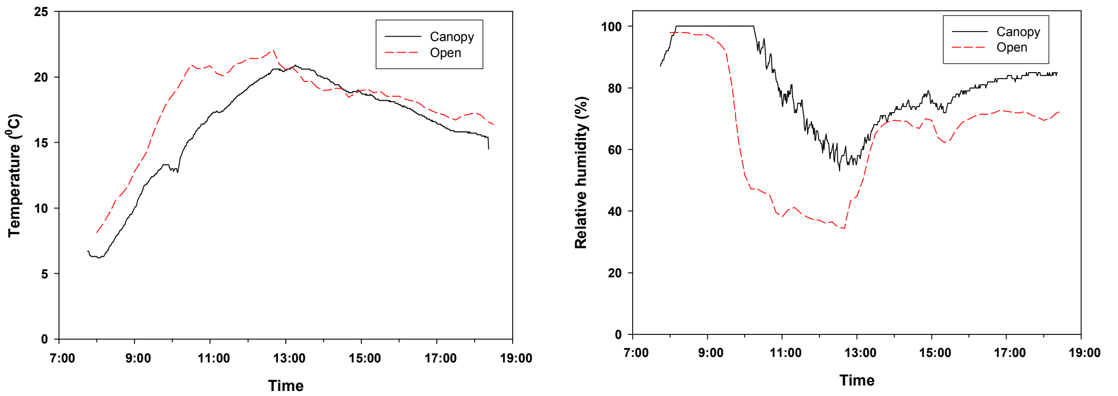


Figure 4.16. Time-series plots of temperature (a) and relative humidity (b) recorded in the open and under the canopy at fuel level for the hourly sampling carried out on 20 March 2007.

Weather conditions on 12 December 2006 (Figure 4.15) were characterised by rapid drying associated with the arrival of a strong northwest wind around late morning/noon. In Canterbury these winds are associated with low relative humidity and high temperature, from the foehn effect of warm and dry air pushing over the Southern Alps mountain ranges onto the Canterbury Plains (Ryan, 1987; Sturman, 2008). There was a rapid increase in temperature and wind speed (19.5°C and 7 km h^{-1} at 12:00 to 29.3°C and 21 km h^{-1} at 13:00) and decrease in relative humidity (74% at 12:00 to 22% at 13:00). However, temperature and relative humidity trends under the canopy indicated differences from the trends in the open. Fuel-level temperature showed a clear increase, and from around 13:30 to 16:00 was higher than that recorded in the open. Fuel-level relative humidity was initially higher in the morning (around 08:00 to 10:30), then was lower than that in the open (10:30 to 12:00), decreased rapidly along with the relative humidity in the open, and was again higher than the humidity recorded in the open (around 13:00 onwards).

The trends for 20 March 2007 (Figure 4.16) indicate that fuel-level temperature remained lower than that in the open until 13:00, when the fuel-level temperature became higher than that in the open until around 15:00. It then dropped to be lower than the temperature in the open for the remainder of the afternoon. Relative humidity was consistently higher throughout the day, although the overall trend was similar to that recorded in the open. These weather conditions were different to those on 12 December 2006, in that the diurnal pattern followed a more 'typical' trend of a building sea breeze (from the east) from late morning into the afternoon, with milder temperatures (maximum open temperature 22.1°C) and relative humidity (minimum 34% in the open) levels throughout the day. The maximum wind speed recorded during the afternoon was 17 km h^{-1}. Overnight conditions prior to sampling on 20 March 2007 were also considerably cooler than on 12 December 2007, with a temperature of 2.8°C at 06:00 and relative humidity of 98% to 08:30 (in the open).

These trends in temperature and relative humidity indicated that the gorse canopy sheltered the elevated dead fuels from the effects of weather conditions in the open, and that the canopy also trapped significant amounts of heat and moisture. Wind speeds recorded under the canopy during both sampling days were seldom higher than

0.5 m s^{-1}, even during the stronger wind events on 12 December 2006 (Section 4.5). Physiological processes such as evapotranspiration probably contributed to the higher relative humidity levels (and to a lesser degree temperature) under the gorse canopy. The nature of the canopy, such as presence and distribution of gaps and canopy 'roughness', would also have had a significant influence on the degree of mixing and entrainment of air into the canopy from winds above (Geiger *et al.*, 2003; Jones, 1996; Oke, 1978). Further research into these processes is required to develop reliable models to predict fuel-level temperature and relative humidity under gorse canopies. Additional and more extensive research should cover site and fuel differences and include measurements of Leaf Area Index (LAI), leaf area density, canopy albedo, density of the canopy and distribution of fuel clumps, wind flow, etc. (refer to the discussion in Section 4.7)

4.5. *Wind speed*

Wind speed was measured at various locations and heights above ground at the Pines Beach study site: 10 m in the open from the weather station for the duration of the study; 2 m and 1.5 m in clearings amongst gorse clumps during fire experiments; and at 1 m above ground under the gorse canopy during the hourly fuel moisture sampling (Section 4.2). Fire danger rating and fire behaviour prediction models used in New Zealand rely on wind speed and direction recorded at weather stations in open clearings at a height of 10 m above ground level (Lawson & Armitage, 2008). For operational application of models using wind speed measured at a height other than 10 m above the ground, this wind speed must be converted to an equivalent 10 m height. Wind speed measured at 1.5-2.0 m above ground in the open can be converted to a 10 m equivalent using a multiplication factor of 1.5 (Lawson & Armitage, 2008; Pearce & Anderson, 2008). The objective of this work was to determine conversion factors for 10m observations to wind speed at fuel-level in gorse fuels, as input into models of fuel moisture and fire development.

Relationships were developed to convert wind speed at 10 m above ground to wind speed at 2 m and 1.5 m in the open and to wind speed under the canopy at the height of the elevated dead fuel layer. Data from different days were treated as separate data series, since the data were not collected consecutively and were therefore not a continuous time series. Sensors were also placed in different locations each day. Analyses to determine wind speed at the various heights from the wind speed at 10 m above the ground were carried out using first-order autoregressive models to account for correlation in the error structure. Models were of the form:

$$(u_x)_t = a + b * (u_{10})_t + \eta_t , \qquad (4.25)$$

where u_x is the wind speed at the various heights (x = 2 m, 1.5 m, 1 m), u_{10} is the wind speed measured at 10 m above ground and:

$$\eta_t = (ar_1) * \eta_{t-1} + \varepsilon_t , \qquad (4.26)$$

with ar_1 the autoregressive parameter.

Attempts to develop a logarithmic wind profile (Monteith & Unsworth, 1990) using the wind speed measurements from 10 m, 2 m and 1.5 m were unsuccessful. This was probably because the wind speed measurements at 1.5 m were influenced by surrounding vegetation – even although measurements were in open gaps, surrounding gorse clumps were around 2 m tall. Measurements at 1 m were underneath the canopy inside the gorse stands. Other influences such as turbulence and effects of canopy roughness and gaps would have influenced the wind speed significantly at the lower heights, and is a complex area that requires significant further research that was beyond the scope of this study (Finnigan, 2000).

Wind speed at 2 m

Wind speed was recorded at 2 m above ground during the fire experiments at Pines Beach using cup anemometers mounted on a portable weather station (refer to Section 4.2 for instrumentation details). The wind speed was recorded at 1-minute intervals, averaged to provide 10-minute average readings to compare against those from the standard weather station recording wind speed at 10 m above ground. Fire experiments were carried out on five separate days: 14 and 15 December 2006, and 15, 16 and 22 March 2007. However, data were only available for three of these days (14 and 15 December 2006, 15 March 2007) due to the portable weather station datalogger failing on the other days.

The regression equations for each of the three data series, of the model form as described in equations (4.25) and (4.26), are contained in Table 4.7 along with the diagnostics comparing their fit to the original data series. In all cases the intercept term (originally included in the autoregressive model) was found to be non-significant. Intercept terms were subsequently specified as 0. This was reasonable, given that a wind speed of 0 m s^{-1} in the open at 10 m should correspond to a wind speed of 0 m s^{-1} at a height of 2 m. Standard errors and p-values associated with the coefficients for the equations in Table 4.7 are shown in Table 4.8. Plots of the autocorrelation functions showed that residuals from the models in Table 4.7 were not serially correlated. Normal quantile plots showed little deviation from normality. The average of the three coefficients for u_{10} was also applied to the data (Table 4.7). Plots of observed against predicted and residuals for of each of the equations in Table 4.7, as well as the function with the average of the three coefficients, are shown in Figure 4.17. The results and plots show that u_2 was predicted reasonably well for most days, including the average conversion factor derived from the three days' coefficients.

Table 4.7. Comparison of first-order autoregressive models derived for each of the three days to predict u_2 based on u_{10} , as well as an average of all three days ('Combined').

Date	14/12/2006	15/12/2006
Equation	$(u_2)_t = 0.4772*(u_{10})_t + \eta_t$;	$(u_2)_t = 0.5365*(u_{10})_t + \eta_t$;
	$\eta_t = 0.3162*\eta_{t-1} + \varepsilon_t$,	$\eta_t = 0.0878*\eta_{t-1} + \varepsilon_t$,
	ε_t ~(0, 0.1938).	ε_t ~(0, 0.2667).
N	29	30
R^2	0.40	0.87
ME	0.01	0.01
RMSE	0.20	0.26

Date	15/03/2007	Combined
Equation	$(u_2)_t = 0.4973*(u_{10})_t + \eta_t$;	$(u_2)_t = 0.5037*(u_{10})_t + \eta_t$;
	$\eta_t = 0.3885*\eta_{t-1} + \varepsilon_t$,	$\eta_t = 0.2642*\eta_{t-1} + \varepsilon_t$,
	ε_t ~(0, 0.1518).	(average of 3 days).
N	32	91
R^2	0.93	0.90
ME	0.02	0.03
RMSE	0.17	0.22

Table 4.8. Standard errors and *p*-values associated with the coefficients for each of the regression equations developed to predict u_2, as shown above.

Date	Variable	Coefficient	Standard error	*p*-value
14/12/2006	*ar1*	0.3162	0.1766	0.04
	u_{10}	0.4772	0.0276	<0.0001
15/12/2006	*ar1*	0.0878	0.1879	0.64
	u_{10}	0.5365	0.0146	<0.0001
15/03/2007	*ar1*	0.3885	0.1810	0.03
	u_{10}	0.4973	0.0202	<0.0001

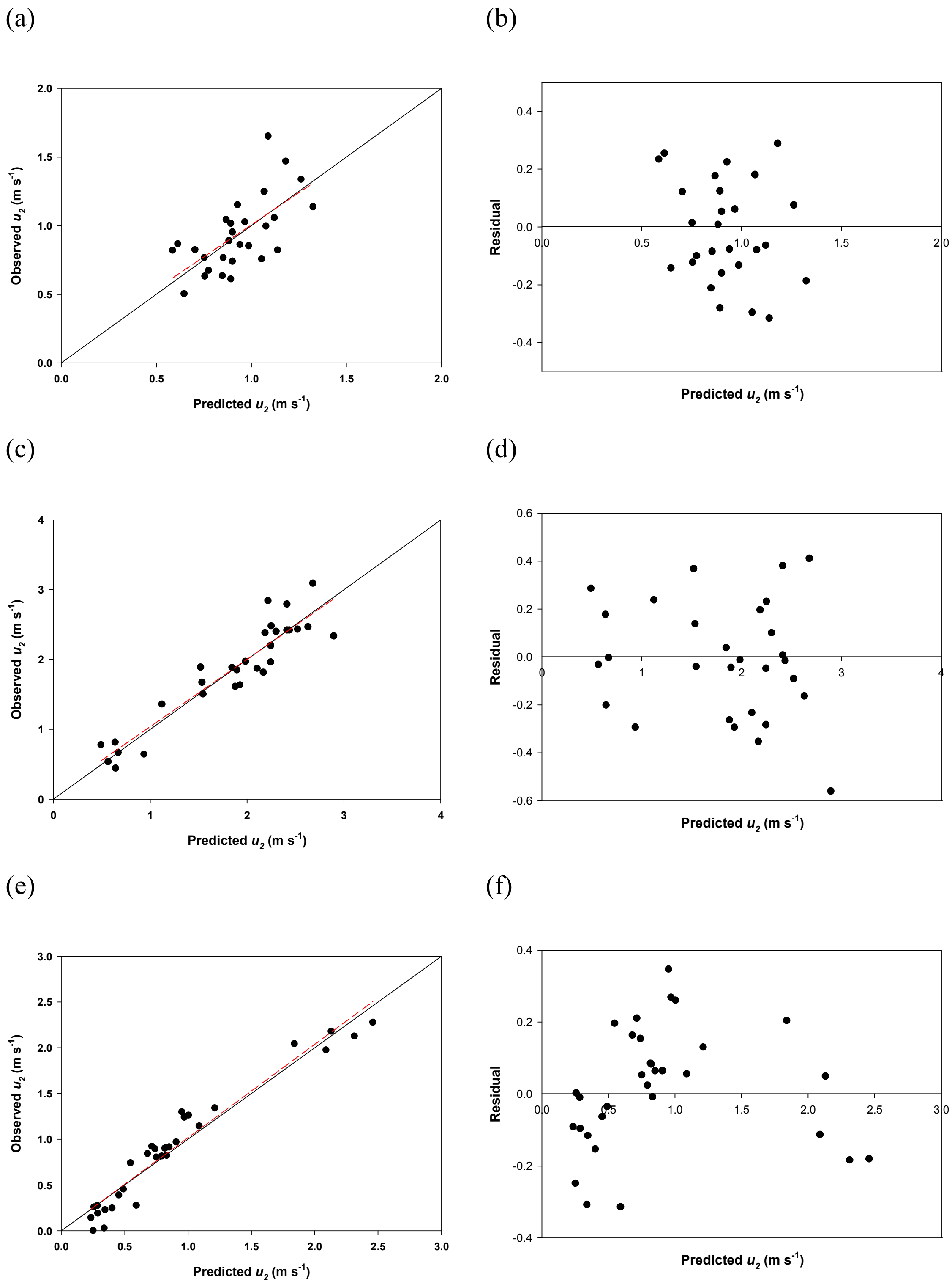
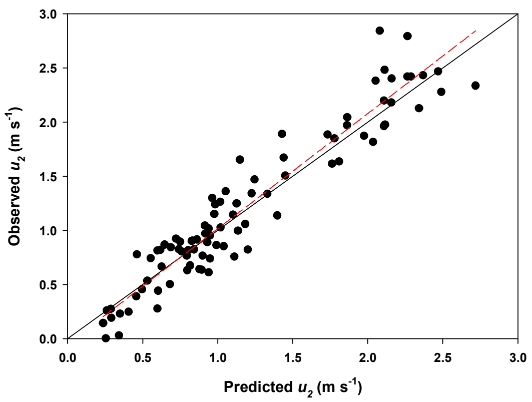


Figure 4.17. Plots of observed against predicted values of u_2 and residuals using the equations from Table 4.3 for: 14 December (a, b); 15 December 2006 (c, d); 15 March 2007 (e, f). Note that patterns in the residuals are due to correlations in the error term.

(g) (h)



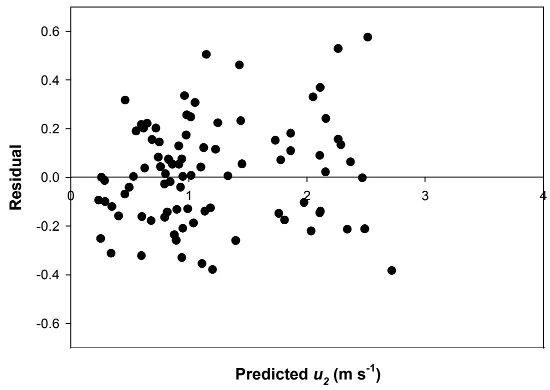


Figure 4.17 (cont). Plots of observed against predicted values (g) of u_2 and residuals (h) using the average of the 3 regression equations in Table 4.3.

Wind speed at 1.5 m

Wind speed was recorded at 1.5 m above the ground during fire experiments at Pines Beach using a sonic anemometer. This was situated in open clearings amongst gorse clumps in the general area where fire experiments were carried out, but at a sufficient distance from experimental plots so that wind speed observations were not influenced by the experimental fires. Wind speed was recorded at 5-second intervals, and then averaged over 10-minute periods to compare against the 10-minute observations collected at 10 m above ground from the weather station. Data were collected for each of the five days of fire experiments: 14 and 15 December 2006; 15, 16 and 22 March 2007.

Regression analyses were carried out following the same approach as used for the 2 m wind speed. First-order autoregressive models, as in equations (4.25) and (4.26), were applied to the data. Each day's data were regarded as separate datasets, creating a total of five series. Initial analyses using first-order autoregressive procedures indicated that the intercept term was significant for three of the five datasets (14 December 2006 and 15 March 2007). However, it was logical that the intercept term should in all cases be 0, since a wind speed of 0 m s^{-1} in the open at 10 m should mean that the wind speed under the canopy will also be 0 m s^{-1}, particularly when the significant sheltering effect of the vegetation canopy is considered (refer to the next section on wind speed under the canopy). In addition, the majority of the datasets produced regression equations with an intercept of 0 (three out of five). First-order autoregressive models with a 0 intercept were therefore fitted to all five datasets. However, specifying a 0 intercept resulted in a poor fit for the models derived from the datasets of 14 December and 15 March. To improve the fit for these two datasets, the autoregressive parameter was fixed at 0.27, the average value of the autoregressive parameters for the models from the three datasets with non-significant intercepts. This produced autoregressive models that fitted the two datasets better and were also of consistent form with the other three models.

The regression equations for each of the five days and a comparison of the fit of these models to the original datasets are shown in Table 4.9. Standard errors and *p*-values associated with the coefficients for the equations in Table 4.9 are shown in Table

4.10. Plots of the autocorrelation functions showed that residuals from these models were not serially correlated. Normal quantile plots showed little deviation from normality, with only a very small number of possible outliers for some of the models. The cause of these outliers was most likely from turbulence in the clearings at the location of the 1.5 m anemometers from the surface roughness and variability of the gorse canopy. An equation that represents the average of the coefficients for u_{10} from each of the five days is also shown in Table 4.9. The plots of observed against predicted values of wind at 1.5 m ($u_{1.5}$) and residuals are shown in Figure 4.18 for each of the regression equations and for the equation based on the average of equations from each of the five days.

The results show that for most days $u_{1.5}$ was predicted reasonably well. However, the model for 14 December 2006 showed a very poor fit to the data, with the model offering little improvement over just using the mean value of the observations. The conversion factor based on the average of the five datasets showed greater variability, but did still provide reasonable predictive power. All of the conversion factors for the equations to predict $u_{1.5}$ from u_{10} (Table 4.7) were higher than those derived for predictions of u_2 from u_{10} (Table 4.3). This was possibly due to differences between the sensors that were used to measure wind speeds at the different heights. Wind speed was measured at 2 m using a standard cup anemometer (Environdata WS30 series) and recorded at 20 s intervals. Wind speed at 1.5 m was measured using sonic anemometers (Gill Instruments Windsonic) that recorded wind speed at 5 s intervals and at a higher sensitivity (0.01 m s^{-1}) compared to the cup anemometer (0.2 m s^{-1}). Both sets of wind speed measurements from the different heights were then averaged over 10 minute intervals to allow comparison with wind speed that was measured at 10 m above ground at the onsite weather station, using a standard cup anemometer (Vector Instruments A101M, sensitivity 0.15 m s^{-1}). Wind speed measurements at 2 m and 10 m using cup anemometers were therefore of coarser resolution than wind speed measured at 1.5 m using the sonic anemometer. The 2 m and 1.5 m anemometers were also situated in different locations at the study site, and also at different distances from the 10 m anemometer.

Table 4.9. Comparison of first-order autoregressive models derived for each of the five days to predict $u_{1.5}$ based on u_{10}, as well as an average of all five days ('Combined').

Date	**14/12/2006**	**15/12/2006**
Equation	$(u_{1.5})_t = 0.9378*(u_{10})_t + \eta_t$; $\eta_t = 0.27*\eta_{t-1} + \varepsilon_t$, ε_t ~(0, 0.3451)	$(u_{1.5})_t = 0.7303*(u_{10})_t + \eta_t$; $\eta_t = 0.3827*\eta_{t-1} + \varepsilon_t$, ε_t ~(0, 0.2501)
N	27	28
R^2	0.07	0.92
ME	0.09	0.03
RMSE	0.41	0.28

Date	**15/03/2007**	**16/03/2007**
Equation	$(u_{1.5})_t = 0.5586*(u_{10})_t + \eta_t$; $\eta_t = 0.27*\eta_{t-1} + \varepsilon_t$, ε_t ~(0, 0.2668)	$(u_{1.5})_t = 0.7423*(u_{10})_t + \eta_t$; $\eta_t = 0.1438*\eta_{t-1} + \varepsilon_t$, ε_t ~(0, 0.2000)
N	27	26
R^2	0.87	0.52
ME	0.19	0.01
RMSE	0.32	0.20

Date	**22/03/2007**	**Combined**
Equation	$(u_{1.5})_t = 0.5482*(u_{10})_t + \eta_t$; $\eta_t = 0.2808*\eta_{t-1} + \varepsilon_t$, ε_t ~(0, 0.1790)	$(u_{1.5})_t = 0.7034*(u_{10})_t + \eta_t$; $\eta_t = 0.2695*\eta_{t-1} + \varepsilon_t$, (average of 5 days)
N	29	137
R^2	0.94	0.73
ME	0.01	0.05
RMSE	0.19	0.45

Table 4.10. Standard errors and *p*-values associated with the coefficients for each of the regression equations developed to predict $u_{1.5}$, as shown in Table 4.9.

Missing values indicate the equations where the autoregressive parameter was fixed at a value of 0.27.

Date	Variable	Coefficient	Standard error	*p*-value
14/12/2006	*ar1*	0.27	-	-
	u_{10}	0.9378	0.04448	<0.0001
15/12/2006	*ar1*	0.3937	0.1723	0.03
	u_{10}	0.7222	0.0207	<0.0001
15/03/2007	*ar1*	0.27	-	-
	u_{10}	0.5586	0.0345	<0.0001
16/03/2007	*ar1*	0.1438	0.2045	0.48
	u_{10}	0.7423	0.0142	<0.0001
22/03/2007	*ar1*	0.2808	0.1919	0.14
	u_{10}	0.5482	0.0146	<0.0001

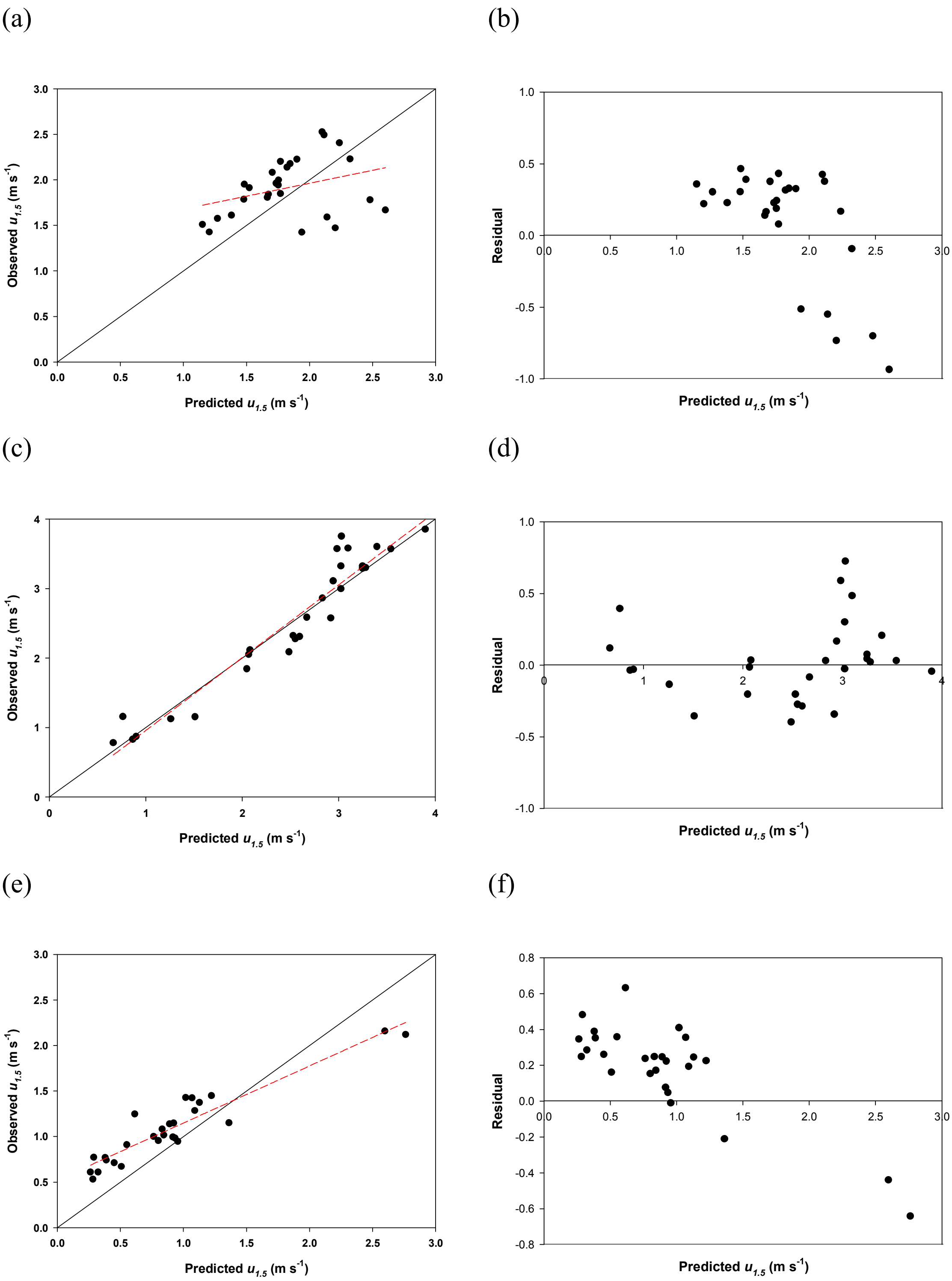


Figure 4.18. Plots of observed against predicted values of $u_{1.5}$ and residuals using the equations shown in Table 4.4 for: 14 December (a, b); 15 December 2006 (c, d); 15 March 2007 (e, f). Note that patterns in the residuals are due to correlations in the error term.

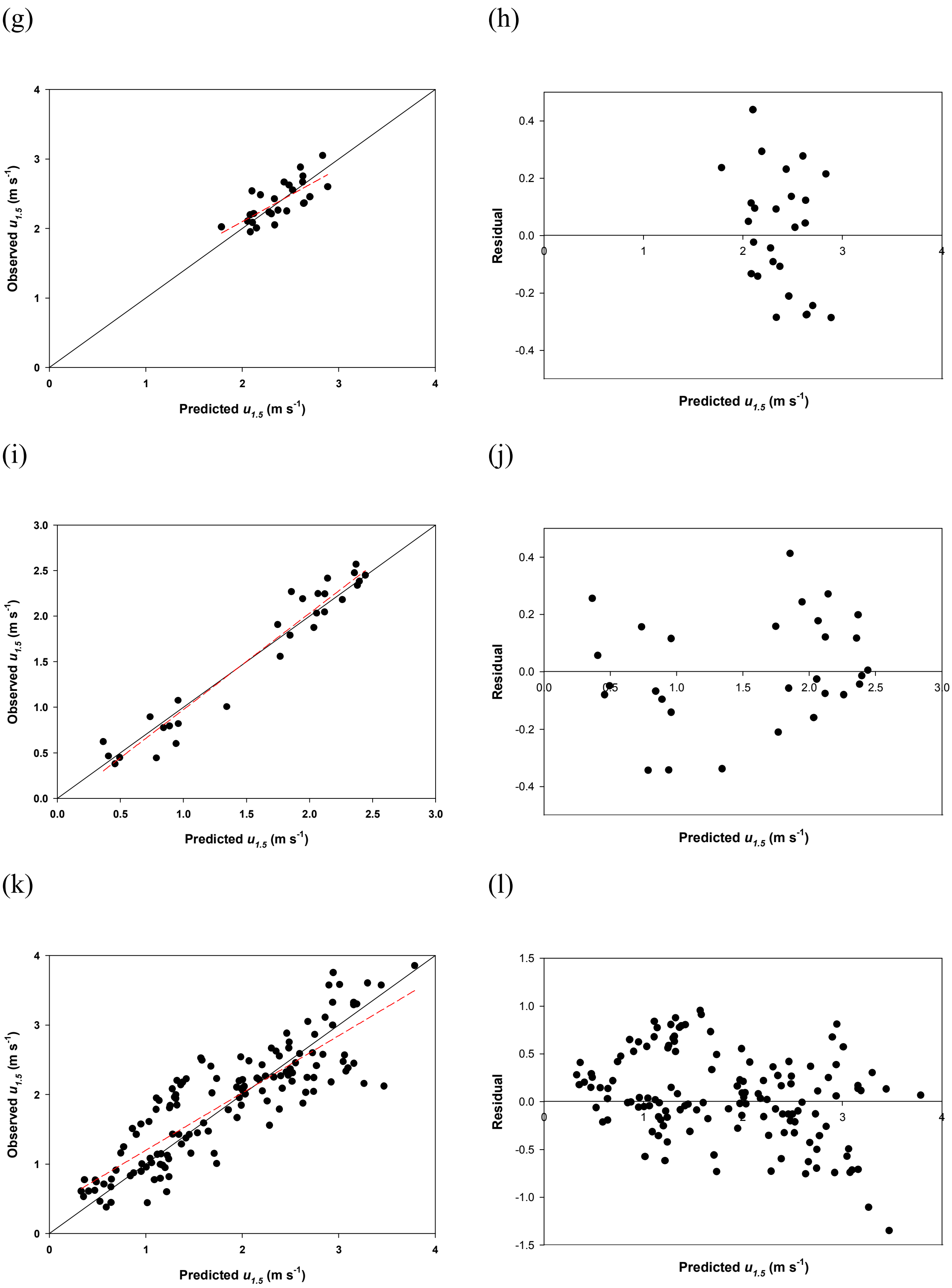


Figure 4.18 (cont). Plots of observed against predicted values of $u_{1.5}$ and residuals using the equations shown in Table 4.4 for: 16 March (g, h); 22 March 2007 (i, j); the average (k, l) of the five regression equations ('Combined' equation in Table 4.4).

Wind speed at 1 m (under the canopy)

Wind speed was measured under the gorse canopy at a height of 1 m above the ground using a sonic anemometer on 12 December 2006 and 20 March 2007 during the hourly fuel moisture sampling. Wind speed was recorded at 5-second intervals, and then averaged over 10-minute periods to compare against the 10-minute wind speed observations from the weather station in the open.

Regression analyses were carried out following the same procedure as for the 2 m and 1.5 m wind data, i.e., applying first-order autoregressive models to the two datasets (equations 4.25 and 4.26). Results from both datasets showed that the intercepts were greater than zero and were significant. When intercepts equal to 0 were specified, the models provided a very poor fit to the data. Similarly, higher-order autoregressive models did not provide any improvements over the first-order autoregressive models with non-zero intercepts. These results contrasted with those from the previous models developed for the 1.5 m wind data and the logic that wind speed at 10 m in the open should equate to a wind speed of 0 m s^{-1} under the canopy. However, these models with non-zero intercepts were retained since they provided the best fit to the two datasets. Since there were intercept terms and because estimates of slope and intercept tend to be correlated, a combined model that averaged the slopes and intercepts of the two days' data was not attempted. Note that these models are not valid for values lower than u_{10} within the dataset (minimum 0.3 m s^{-1}). It was not possible to improve these relationships any further because the limited amount and range of data available. The model to predict wind speed under the canopy at 1 m height above ground (u_1) from wind speed at 10 m in the open (u_{10}) for the data from 12 December 2006 was:

$$\left(u_1\right)_t = 0.1953 + 0.0529 * (u_{10})_t + \eta_t , \qquad (4.27)$$

where

$$\eta_t = 0.486 * \eta_{t-1} + \varepsilon_t , \qquad (4.28)$$

with ε_t normally distributed with mean 0 and standard deviation 0.0378. Standard errors and p-values associated with the coefficients for equations (4.27) and (4.28) are shown in Table 4.11. The plot of the autocorrelation function showed that model residuals were not serially correlated, and the normal quantile plot showed only slight deviation from normality. This was most likely associated with gusty conditions during the early afternoon period when the wind speed increased markedly in the open from the northwest winds. Plots of observed against predicted values of u_1 and residuals are shown in Figure 4.19. The model provided a reasonable fit to the data ($R^2 = 0.95$, ME = 0.0004, RMSE = 0.04).

(a) (b)

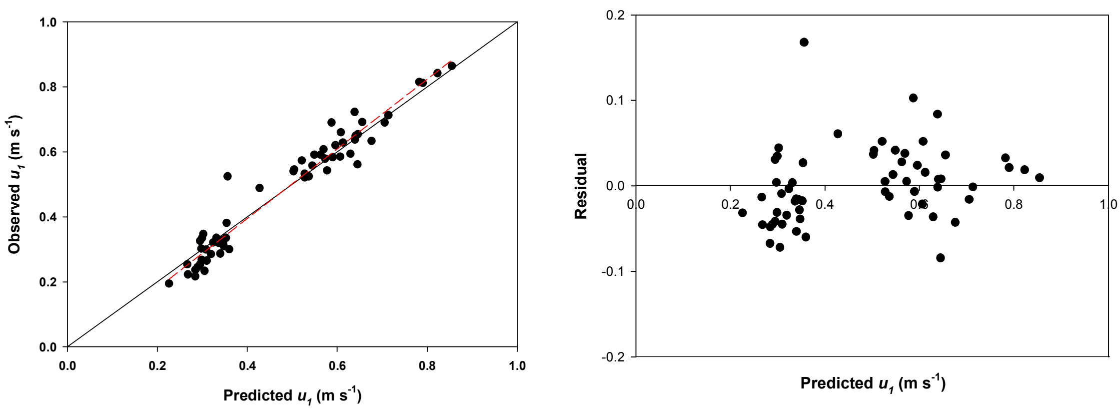


Figure 4.19. Plots of observed against predicted values of u_1 (a) and residuals (b) for 12 December 2006 using equations (4.27) and (4.28). Note that patterns in the residuals are due to correlations in the error term.

The model to predict u_1 for the data from 20 March 2007 was:

$$(u_1)_t = 0.3537 + 0.0382 * (u_{10})_t + \eta_t, \qquad (4.29)$$

where

$$\eta_t = 0.9341 * \eta_{t-1} + \varepsilon_t, \qquad (4.30)$$

with ε_t normally distributed with mean 0 and standard deviation 0.0527. Standard errors and p-values associated with the coefficients for equations (4.29) and (4.30) are shown in Table 4.11. The plot of the autocorrelation function showed that model residuals were not serially correlated, but the normal quantile plot indicated some minor deviation from normality. This was again most likely associated with increasing wind speeds during the early afternoon period from the development of the sea breeze. Plots of observed against predicted values of u_1 and residuals are shown in Figure 4.20. The model provided a less reliable fit to the data, with significantly weaker predictive power than the model for 12 December 2006 ($R^2 = 0.61$, ME = 0.02, RMSE = 0.15).

(a) (b)

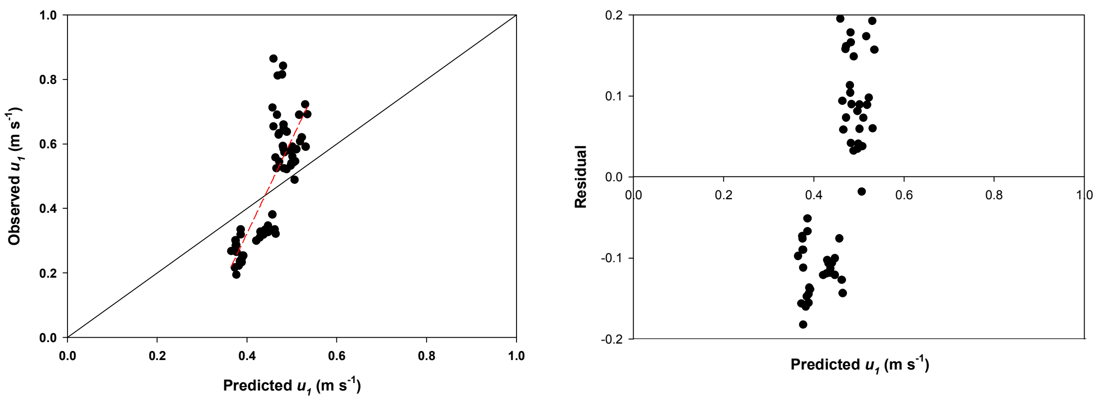


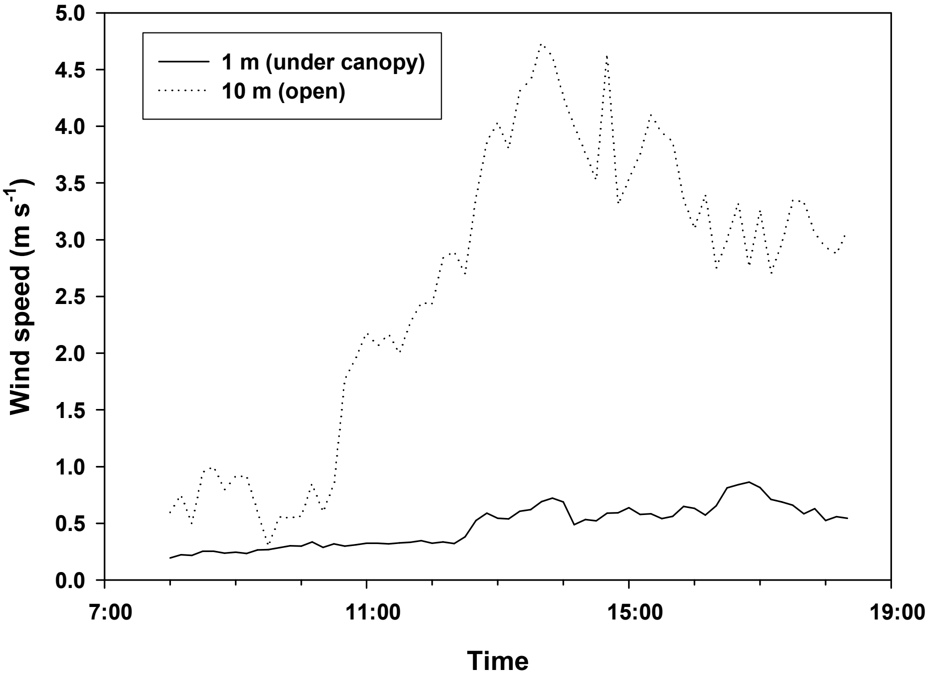
Figure 4.20. Plots of observed against predicted values of u_1 (a) and residuals (b) for 20 March 2007 using equations (4.29) and (4.30). Note that patterns in the residuals are due to correlations in the error term.

Table 4.11. Standard errors and *p*-values associated with the coefficients for each of the regression equations developed to predict u_1.

Equation	Date	Variable	Coefficient	Standard error	*p*-value
4.28	12 Dec 06	*ar1*	0.486	0.169	0.004
		Intercept	0.1953	0.0230	<0.0001
4.27		u_{10}	0.0529	0.0041	<0.0001
4.30	20 Mar 07	*ar1*	0.9341	0.0441	<0.0001
		Intercept	0.3537	0.0934	0.0002
4.29		u_{10}	0.0382	0.0188	0.04

Another problem was the lack of response in wind speed under the canopy compared to significant changes observed in the open wind speed. On both days the wind speed increased significantly in the open during the afternoons, but the response under the canopy was minimal with only slight increases evident (Figure 4.21). This suggests that the canopy had a significant role in sheltering the elevated dead fuel layer and lower layers (near-surface fuels and surface litter) from the wind in the open. On 12 December 2006 the average wind speed under the canopy was 0.48 m s^{-1} (±0.19), compared to an average of 5.3 m s^{-1} (±3.19) in the open. On 20 March 2007, average wind speed under the canopy was again 0.48 m s^{-1} (±0.18), compared to an average of 2.6 m s^{-1} (±1.30) in the open. Wind speeds were different for these two days, with significantly stronger wind speeds in the open on 12 December 2006. However, there was little difference in the wind speeds recorded under the canopy (Figure 4.21).

(a)



(b)

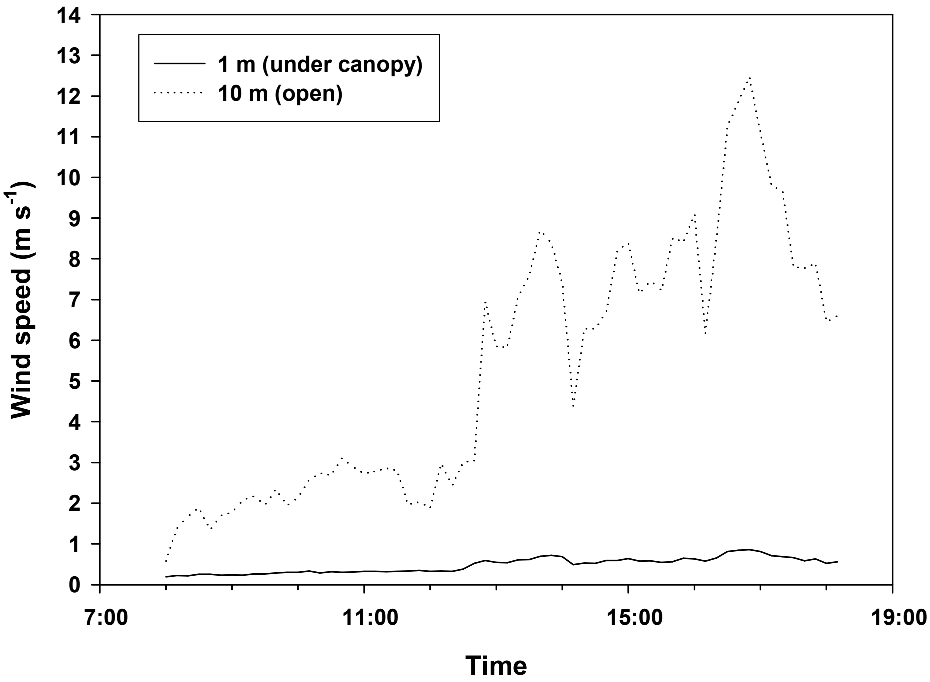


Figure 4.21. Time-series plots of wind speeds measured under the canopy (at 1 m) and in the open (at 10 m) for 12 December 2006 (a) and 20 March 2007 (b).

4.6. Rain

A study was carried out to understand the interception of rainfall by the gorse canopy. This is an important factor that affects the moisture content of elevated dead fuels. The Fine Fuel Moisture Code (FFMC) of the Fire Weather Index (FWI) System has a threshold of 0.6 mm. This means that 24-hour rainfall amounts (to 12:00 LST) of less than 0.6 mm are assumed not to influence the moisture content of the dead fine fuels on the surface layer. This threshold value was derived from the coniferous forest ‘reference’ fuel type upon which the system is based (Section 2.5.3.3) (Van Wagner, 1987).

The study was carried out from 4 December 2007 to 12 May 2008 at the Pines beach study site. Two self-logging tipping-bucket rain gauges (Onset RG3-M with Hobo RG-3M Pendant Event Logger) were placed at random locations under the gorse canopy (Figure 4.22) within the area where the fuel moisture sampling was carried out. The rain gauges were moved to different locations under the canopy at regular intervals throughout the study period. The rain gauges recorded rainfall amounts in units of 0.2 mm. They were placed on a 30 x 30 cm concrete paving stone to provide a level surface. Some problems were encountered during the study period, including the rain gauges being knocked over (probably by livestock or rabbits) and clogging of the buckets with debris from the canopy that prevented rainfall from passing through the bottom of the bucket to tip the gauge. This mostly occurred after very heavy rainfall events that caused significant amounts of fine particles to dislodge from the canopy and gather in the bucket. Notwithstanding these problems, sufficient data were collected for analysis. The duration of each rainfall event was determined by a visual examination of the dataset and the end point of the rainfall event was identified when it was clear that no further rainfall was received in either the open or under the canopy for several hours after the last reading.

Figure 4.22. Rain gauges located under the gorse canopy.

An initial plot of the surface (under-canopy) rainfall versus the open rainfall measured at the weather station located in the open showed that the relationship was curvilinear. A second-order polynomial relationship fitted the data well (Figure 4.23) (for the predicted versus observed values, $R^2 = 0.996$, ME = 0.04, RMSE = 0.43). However, further data at higher rainfall values are required to adequately validate this relationship.

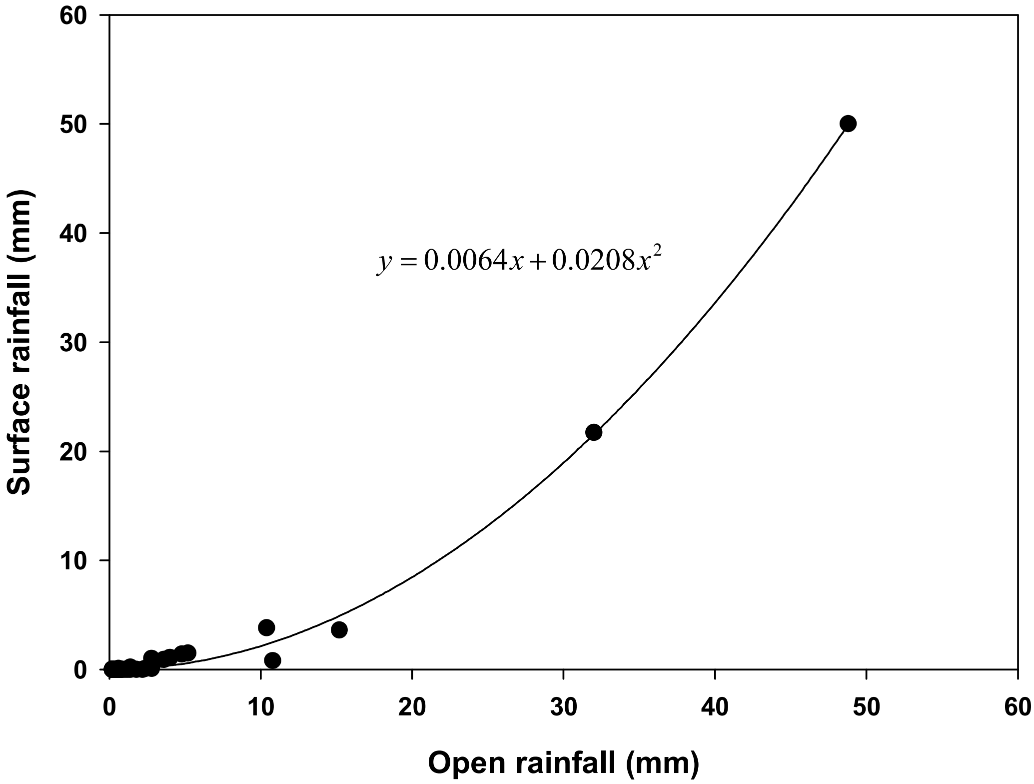


Figure 4.23. Plot of surface (under-canopy) rainfall against open rainfall, with the polynomial relationship fitted.

The difference between the rainfall received in the open and that at the surface level under the canopy was calculated. This indicated the amount of rainfall that was intercepted by the canopy for each rainfall event, and also the potential water storage capacity of the canopy layer. A polynomial function was fitted to the data and a parabolic function provided the best fit to the data (Figure 4.24) (for the predicted versus observed values, R^2 = 0.97, ME = -0.04, RMSE = 0.43). Therefore, once the amount of rainfall in the open exceeded approximately 48 mm rainfall would begin to pass through the canopy without any interception, meaning that the surface under the gorse canopy would receive the same amount of rainfall as the rain gauge in the open. This meant that the canopy had exceeded its maximum water storage and was no longer able to intercept any rainfall. The negative difference in Figure 4.24 for rainfall amounts at 48 mm is probably from additional stored (intercepted) rainfall in the canopy dripping into the rain gauge, causing a higher reading under the canopy than in the open.

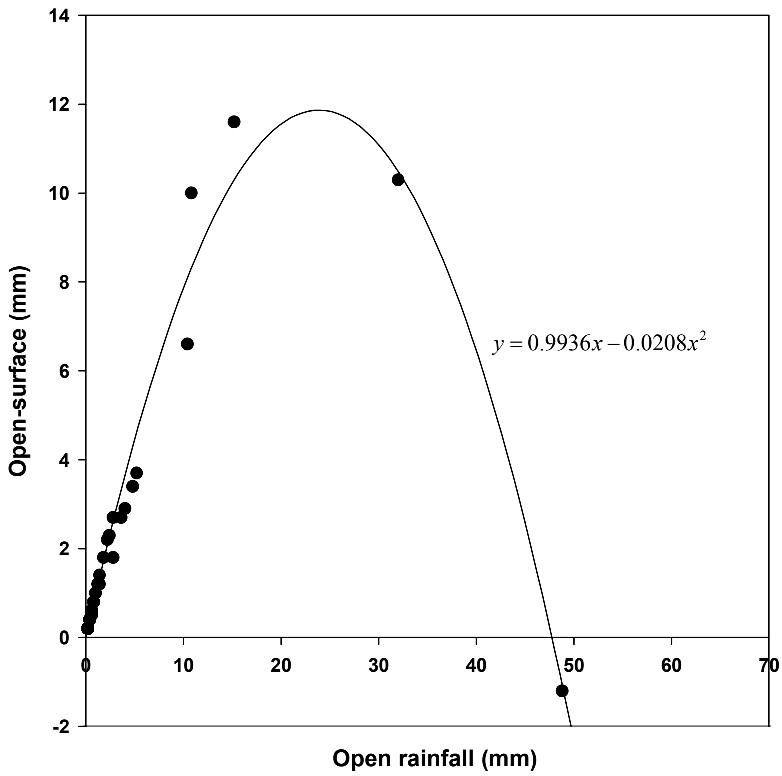


Figure 4.24. Plot of the difference in rainfall between the open and under the canopy (surface) against rainfall received in the open, with a parabola curve fitted to the data.

The dataset and observations from field visits to download the rain gauges during the study were used to determine a rainfall threshold below which rainfall would not affect the moisture content of the elevated dead fuels. This value was estimated at 0.2 mm and means that rainfall amounts of 0.2 mm will be mostly intercepted by the top (live) canopy layer and not reach the dead elevated fine fuel.

This study did not account for the cumulative effect of rainfall and rainfall duration or intensity. Long-duration rainfall events of light drizzle will eventually reach the point where sufficient precipitation gathers in the live canopy layer to reach the elevated dead layer. Intercepted rainfall can also be transported towards and down stems of shrub fuels (Bhark & Small, 2003). Rainfall interception and throughfall under the canopy is highly variable spatially, and further research across a number of locations with a larger number of rain gauges that cover a larger number of rainfall events is required to validate the rainfall thresholds in gorse canopies.

4.7. Discussion

These analyses provided insight into the micrometeorology within and under the canopy layer in gorse fuel complexes. Whilst the small datasets were a limitation to developing adequate models for the various weather variables, the results highlighted significant differences between meteorological conditions at fuel level and those in the open. These findings are significant, since fire behaviour models and fire danger rating systems mostly rely on meteorological inputs from weather stations in the open with little modification for conditions at fuel level. This is particularly the case for shrub fuels. Analyses also provided useful indications of the processes that drive meteorological conditions under the canopy, and identified aspects for further research. Purely empirical relationships for these variables are of limited use and applicability beyond the conditions under which the models were developed. There are complex physiological processes that influence meteorological conditions under the canopy that need to be measured and modelled.

The models of Byram and Jemison (1943) and Van Wagner (1969) did not predict fuel-level temperature and relative humidity well, largely due to the fact that these models assume heating of fuels by direct solar radiation. Whilst the lag and regression modelling approaches provided promising results, these models could not be applied generally to gorse fuels due to the limited dataset that consisted of measurements from just two days. The linear regression results showed that solar radiation has a significant, but small, influence on fuel-level temperature, but no effect of wind speed could be determined. These results will of course only be applicable to gorse with a similar fuel structure and site conditions as at the Pines Beach study site. Examination of time series for fuel-level and air temperature and relative humidity indicated that physiological processes (such as evapotranspiration) and other complex micrometeorological factors (such as canopy roughness and the degree of mixing with the air above the canopy) are important factors that influence temperature and humidity under the canopy. Considerable further research is required to develop adequate meteorological models for fuel-level conditions that can be applied more extensively to gorse and other shrub fuels across the country.

Results from modelling solar radiation, wind speed and rainfall again suggest that further data and research are required. There is a large body of knowledge on the micrometeorology of forests, crops and grasslands (e.g., Geiger *et al.*, 2003; Jones, 1996; Monteith & Unsworth, 1990; Oke, 1978), but that comparatively little research has been carried out into micrometeorology of shrub fuels. Recent work in heathland fuels of the Sydney Basin in Australia found similar difficulties in modelling fuel-level meteorology to predict fuel moisture content (Pippen, 2007).

These results provided useful information to incorporate into models of fuel moisture and thresholds for fire development. Very little of the solar radiation received in the open (2-3%) penetrated through the gorse canopy to reach the level of the elevated dead fuels. These results compare with the very low levels of transmittance recorded in dense forests (e.g., Black & Kelliher, 1989; Shuttleworth, 1989). There was also very little response in wind speeds under the canopy, compared to significant variability in the 10 m open wind speed. The average wind speed under the canopy was 0.5 m s^{-1} for both days under very different conditions in the open. The main influence of wind speed on fuel moisture content may be from transportation of air masses with significantly different moisture contents. This is particularly the case with the northwest wind in Canterbury that brings dry and warm air across the plains from the Southern Alps mountain ranges in the west (foehn effect), and significantly changes the fuel moisture content and elevates fire danger rapidly. Rainfall studies showed that the current rainfall threshold of 0.6 mm applied to the Fine Fuel Moisture Code of the FWI System is probably not valid for the elevated dead fuel layer in gorse (a threshold of 0.2 mm was recommended from the field study). Further detailed studies into rainfall interception and storage by the shrub canopy are required that account for interception, drainage through the canopy and spatial variability.

Spatial variability under the canopy is significant, and further research needs to be conducted on a larger scale with more instrumentation over longer periods of time to fully understand these complex processes. These studies should also incorporate the broader body of knowledge on vegetation micrometeorology, and include measurements of LAI, canopy density, heat flux, evapotranspiration, turbulent processes, etc. Such research was beyond the scope of this study, but is highly recommended to improve the prediction of fuel level conditions under shrub canopies.

Chapter 5:
Predicting elevated dead fuel moisture[10]

5.1. Introduction

Fuel moisture influences all aspects of fire behaviour and combustion, including ease of ignition, availability of fuel for combustion and rates of combustion (Brown & Davis, 1973; Pyne *et al.*, 1996). Fuel moisture therefore forms a central component of fire danger rating systems and many fire behaviour models, and its accurate estimation is essential for fire management decision-making. Dead fine fuels are particularly important for fire development and spread.

Gorse *(Ulex europaeus*) is an evergreen, leguminous shrub. The genus (Fabaceae) comprises around 20 species, with *U.europaeus* the most common and widespread. It is prickly, with sharp spines growing in the axils of leaves (Hoshovsky, 1989; Zabkiewicz, 1975). Gorse is a highly successful and fast-growing shrub species with a lifespan of approximately 30 years. It has nitrogen-fixing bacteria in nodules on the roots, is able to sprout from the stem and even from roots if cut or burned to ground level, and produces vast amounts of seed that can remain viable for over 30 years in the soil (Tarayre *et al.*, 2007; Zabkiewicz, 1975). The natural distribution of gorse is predominantly across central and western Europe, where fire plays an important role in these and other shrublands (Di Castri, 1981; Gimingham & Chapman, 1979). However, it has spread and become a serious weed problem around the world, for example in Hawaii, Australia, Chile, Costa Rica, New Zealand and the Atlantic coastal areas of North America (Hoshovsky, 1989; Tarayre *et al.*, 2007; Zabkiewicz, 1975). In New Zealand, it covers approximately 700,000 ha (Blaschke *et al.*, 1981) – nearly 3% of the land area of the country.

Gorse can represent a significant fire hazard, with large amounts of elevated dead fine fuels suspended from branches within the canopy layer and large amounts of dead

[10] The work presented in this chapter has been accepted for publication by the Canadian Journal of Forest Research. It is largely unchanged from the submitted manuscript and therefore some repetition in the background information will be evident.

litter on the ground (Figure 5.1). Total fuel loads of 46-52 t ha^{-1} have been reported for *U.europaeus* shrublands in Spain (Vega *et al.*, 2005). Sampling in New Zealand found total fuel loads of 26-74 t ha^{-1} across a range of 58 sites with significant variability in fuel age, cover and climate zones. The elevated dead fine fuel loads (fuel particles less than 5 mm diameter) represented on average 33% of the total available fuel load for each sample plot. Fires in gorse, like other shrub fuels, can often burn at very high rates of spread and extreme fire intensities under levels of fire danger that would not be considered extreme in other fuel types, such as forest and grass (De Luis *et al.*, 2004; Fernandes, 1998; Fogarty, 1996). In New Zealand, fires in shrub fuels (including gorse) account for around 40% of the total annual area burned (Anderson *et al.*, 2008). During experiments carried out in New Zealand, some fires in gorse have been observed to develop and spread in the elevated dead fuel layer, independently of the surface litter layer (Scion, unpubl. data; Anderson & Anderson[11]). Observations and anecdotal evidence from prescribed burning operations and wildfires also corroborate this finding (pers. obs.).

Most fuel moisture models have been developed for fire danger rating and fire behaviour prediction and are designed to determine the moisture content of fine fuels in surface litter layers (or grasses and low shrubs), not of elevated dead fine fuels (Marsden-Smedley & Catchpole, 2001). These elevated fuels can be more flammable and carry fire easier than lower layers, including surface litter, since they are more exposed and aerated and dry quicker. Difficulties with the development of reliable fire danger and fire spread models in New Zealand shrub fuels are partly due to an inability to accurately model elevated dead fine fuel moisture content (Anderson, 2009; Fogarty *et al.*, 1998). Similar problems have been encountered in European (Fernandes, 2001; Fernandes, 1998) and Australian shrub fuels (Catchpole *et al.*, 1998). The New Zealand Fire Danger Rating System is based on the Canadian Forest Fire Danger Rating System (CFFDRS) (Anderson, 2004; Stocks *et al.*, 1989), and it is important that new fuel moisture models are compatible with the current national system that is used operationally (http://nrfa.fire.org.nz/Firenet/Regions/Rural/FireWeather). There has also been a strong focus on developing and adapting the CFFDRS, in particular the Fire Weather

[11] Anderson, S.A.J. and Anderson, W.R. Ignition and fire spread thresholds in gorse (*Ulex europaeus*). Manuscript submitted to the International Journal of Wildland Fire.

Index (FWI) System component, for fire behaviour and fire danger rating purposes in forests and shrublands of Southern Europe (Rainha & Fernandes, 2002; San-Miguel-Ayanz *et al.*, 2003; Viegas *et al.*, 2001), and heather moorlands of the United Kingdom (Davies *et al.*, 2006; Kitchen *et al.*, 2006).

Figure 5.1. Gorse shrubland on the outskirts of Wellington, New Zealand, showing a profile with dead fine fuel suspended underneath the green canopy (Source: Scion).

The overall objective of this study was to develop a suitable moisture prediction model for the elevated dead fine fuel layer in gorse. The first aim was to test the applicability of the Fine Fuel Moisture Code (FFMC) of the FWI System, in its current form, to predict fuel moisture for this layer. The second aim was to attempt simple modifications of the FFMC using regression modelling, following the approach of Wotton and Beverly (2007). The final aim was to develop an alternative approach that incorporated the fuel response times and equilibrium moisture contents specific to this fuel type.

5.2. *Background*

5.2.1. Equilibrium fuel moisture content and response time

The equilibrium moisture content (EMC) of a fine fuel particle is the moisture content that the fuel particle will approach if exposed to constant temperature and relative humidity for an indefinite period of time. Having reached this moisture content, the fuel particle is said to be in equilibrium with its surrounding conditions (Pyne *et al.*, 1996). EMC is determined by: fuel temperature and air humidity; fuel characteristics such as surface area to volume ratio, density, shape, the nature of fuel coatings and weathering (ageing) effects; and whether the fuel particle has been gaining (adsorbing) or losing (desorbing) moisture (Anderson, 1990; Catchpole *et al.*, 2001).

Using diffusion theory, the following differential equation approximates the change in moisture content from adsorption and desorption processes for a fuel particle of small diameter (Byram 1963, in Catchpole *et al.*, 2001):

$$\frac{dm}{dt} = -\frac{m-q}{\tau}, \qquad (5.1)$$

where m is the fuel moisture content at time t, q is the EMC and τ is the response time of the fuel. The response time is the time taken for a fuel particle to achieve approximately 63% of the difference between its initial moisture content and the EMC. Refer to Table 5.4 for a listing of all of the symbols referred to in this and subsequent equations.

5.2.2. The Canadian Fine Fuel Moisture Code

The FWI System indicates the moisture content of three main layers of dead forest floor fuels and combines these with the influence of wind speed to estimate fire behaviour potential. The system uses Canadian mature jack (*Pinus banksiana*) and lodgepole (*Pinus contorta*) pine stands on level terrain as its reference fuel type. It comprises six numerical ratings: three fuel moisture codes and three fire behaviour indices. For each of the codes, moisture is added after rain and reduced after each day's drying. All codes have built-in time lags and rainfall thresholds (below which precipitation will not lower the value). Higher values of codes correspond to lower moisture contents (Stocks *et al.*, 1989). The system uses standard, daily weather inputs of noon temperature, relative humidity, wind speed and rainfall accumulation.

The Fine Fuel Moisture Code (FFMC) represents the moisture content of fine surface litter and other fine fuels on the forest floor, and indicates ignition potential. It is based on the value of the previous time step's moisture content and the current EMC. The FWI System calculates outputs daily at 12:00 local standard time (LST), to represent conditions during the peak afternoon burning period of around 16:00 LST (Van Wagner, 1987). There are also methods in place to compute outputs on an hourly basis that provide more frequent and updated estimates of fire potential (Alexander *et al.*, 1984; Lawson *et al.*, 1996). A complete description of the FFMC is contained in Van Wagner (1987).

The hourly FFMC is calculated by determining the EMC under drying (E_d) and wetting (E_w) conditions. The FFMC is the only FWI System code that allows for a variable EMC (Van Wagner, 1975). Log drying (k_d) and log wetting (k_w) rates are calculated based on temperature and intermediate variables k_a (for k_d) and k_b (for k_w), which are in turn calculated from relative humidity and wind speed. Moisture content (m) is then calculated from EMC, the previous hour's moisture content (m_0) and either k_d or k_w. This value of m is converted to FFMC code form. Moisture is added to m_0 where rainfall occurs (Alexander *et al.*, 1984; Van Wagner, 1987).

5.2.3. Response time and fuel moisture content from field data

Catchpole *et al.* (2001) developed a method to determine τ and calculate m using field data. Solving equation (5.1) for any time interval allows calculation of m. To approximate the EMC as a function of time, t, a constant centred piecewise approximation was used in the time interval $(t-\delta t/2, t+\delta t/2)$, where δt represents a small time period. Incorporating this piecewise approximation of EMC into the solution of equation (5.1) gives the following equation to determine m:

$$m = \lambda^2 m_0 + \lambda(1-\lambda)q_0 + (1-\lambda)q\,, \qquad (5.2)$$

where $\lambda = \exp\left(-\delta t/(2\tau)\right)$, m_0 is the previous hour's moisture content, q_0 is the previous hour's EMC, and q is the current EMC.

The EMC was determined using the approach of Nelson (1984), modelling EMC as a linear function of the change in the logarithm of the Gibbs free energy of the fuel particle, ln(ΔG). This is estimated using the temperature and relative humidity of the fuel particle (or values at fuel level). The formula to calculate EMC is:

$$q = a + b \ln \Delta G = a + b \ln\left\{-\frac{RT}{M}\log H\right\}, \tag{5.3}$$

where a and b are constants specific to a fuel type that vary depending on whether the fuel is adsorbing or desorbing moisture, R is the universal gas constant (1.987 units), T is the temperature (K), M is the molecular weight of water (18.0153 g Mol^{-1}), and H is relative humidity (expressed as a fraction). The model is specified by fitting a, b, and τ to observations of moisture content and weather. This approach is generally not applicable for fuels above the fibre saturation point, which is considered to be around 35% moisture content (Cheney, 1981).

There are some differences between this model and the FFMC procedure. One is that Van Wagner (1987) used an uncentred piecewise approximation to determine EMC, rather than the centred approximation for this model. The EMC equations in the FFMC also have a different form to equation (5.3). Catchpole *et al.* (2001) also used a constant t (differing only between adsorption and desorption), but this constraint could be relaxed.

5.3. Methods and results

5.3.1. Study area

The study site was located in the area of Pines Beach, a small community approximately 20 km north of Christchurch in the South Island of New Zealand (43°21′S, 172°41′E). The site covered an area of c. 80 ha and was located on farm land approximately 1.5 km from the coast and used predominantly for dairy farming. Vegetation consisted mostly of large areas of mature gorse, ranging from small clumps of a few metres in diameter to large continuous areas, and pasture grasses. Gorse stands contained mature plants, with average heights from 2.0-2.5 m. Stands were uniform, with continuous closed-canopy cover and a layer of elevated dead fine fuels under the canopy down to approximately 0.5 m above ground level. Below this layer there was a near-surface layer, comprising dead gorse needles suspended on stems and branches. There was a continuous layer of surface litter, above a duff layer of needles in various stages of decomposition of around 5 cm depth. Fuel loads were estimated to be from 34.8-39.5 t ha^{-1}, using the fuel load model of Fogarty and Pearce (2000). The land was bordered by other farm land and a mature *Pinus radiata* plantation. The topography of the general area was flat and uniform, with soils described as Yellow-brown Sands, comprising coastal sand and gravel with little or no topsoil differentiation (New Zealand Soil Bureau, 1968).

A weather station was erected at the site for the duration of this study, measuring: rainfall in mm (hourly) at ground level; temperature (°C), relative humidity (%) and solar radiation (W m^{-2}) at 10-minute intervals at a height of 1.5 m above ground; and the 10-minute average wind speed (km h^{-1}) and direction at a height of 10 m above ground. The weather station was located in an open clearing, within 300 m of the areas from where fuel moisture samples were collected. Weather readings from this station were used to calculate hourly values of the FWI System for the duration of the study, as per Alexander *et al.* (1984). The FWI System calculations were initiated with starting values of FWI System fuel moisture codes (FFMC, Duff Moisture Code and Drought Code) from a permanent fire weather station located nearby (Bottle Lake, approximately 12 km south of the study site).

5.3.2. Field sampling

Destructive sampling of fuel moisture was carried out using two approaches. All samples were collected at a distance of 5-15 m inside stands of mature gorse to avoid edge effects. The first approach involved daily collection of five samples of elevated dead gorse needles and small twigs (diameter less than 0.5 mm) of approximately 20-25 g (dry weight). These fuels were collected from approximately 0.5 m above the ground to just underneath the green (live) foliage that formed part of the canopy, typically at a height of 1.5 m. Samples were collected during the afternoon, roughly between 15:00 and 16:00 to reflect conditions during the 'peak afternoon' burning period that the FWI System codes and indices represent (Van Wagner, 1987). Sampling was carried out over consecutive days, as far as weather and resources allowed. Sampling did take place following rainfall, but not during rain events or where there was obvious surface moisture on the fuels from precipitation. Sampling took place during two periods, 6 March to 12 April 2006 (n = 28) representing late summer/early autumn conditions and 29 November to 12 December 2006 (n = 14), representing early summer conditions. These two periods were chosen to track daily variation and include both dry and wet conditions, and to provide sufficient data to evaluate the daily response of the FFMC under different conditions. A summary of the sampled moisture content and weather data for these two periods is contained in Table 5.1.

Table 5.1. Summary of sampled fuel moisture and weather data for the two study periods during March/April 2006 (n = 28) and November/December 2006 (n = 14). Weather observations were taken at the onsite weather station in the open.

	Elevated *m* (%)		**Temp (°C)**		**Relative humidity (%)**		**Wind speed (km h^{-1})**		**Rainfall (mm)**		**FFMC**	
	Mar	Nov	Mar	Nov	Mar	Nov	Mar	Nov	Mar	Nov	Mar	Nov
Mean	18.2	19.2	16.9	16.2	58.4	60.1	15.1	18.6	1.2	1.3	76.6	72.5
Median	14.6	15.5	16.1	14.9	62.1	64.6	14.1	18.5	0.0	0.1	81.4	79.2
Max	85.8	49.6	24.5	26.2	82.0	85.6	26.9	37.6	16.6	8.2	90.0	88.8
Min	8.5	8.5	13.8	10.9	25.3	26.8	7.4	10.3	0.0	0.0	33.4	48.4

Samples were sealed in airtight containers and weighed (wet weight), dried in an oven at 105°C for a minimum of 24 hours, and then weighed again (dry weight). Fuel moisture content (*m*) was calculated as a percentage of dry weight. Patterns of fuel wetting were observed to be variable under the gorse canopy, as a result of patchiness of the canopy that influenced rainfall accumulation and penetration down to the elevated dead fuel layer. To account for this variability of rainfall interception and to minimise the influence of extreme values for each sampling event, the 60% trimmed mean was taken to provide a more robust estimate of the average moisture content for that day's sample. This excluded the highest and lowest observations from the five samples. The trimmed mean standard error was then calculated to indicate the uncertainty of the trimmed mean estimate, using the Winsorized standard deviation (Heckert, 2003a, 2003b; Tukey & McLaughlin, 1963). Standard errors were mostly less than one, notable exceptions being on sample days following rainfall when there was significant variability between individual samples (Figure 5.2).

(a) (b)

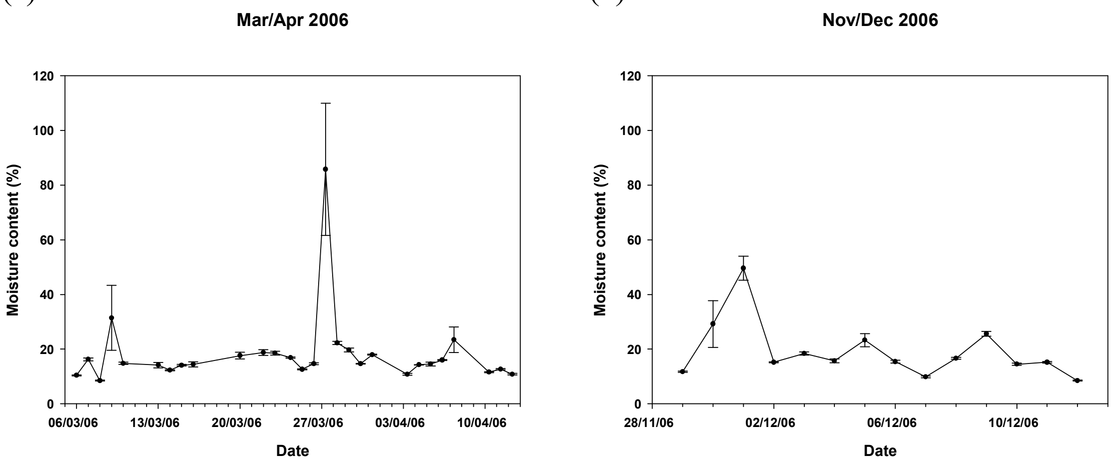


Figure 5.2. Time-series plots of moisture content sampled daily during March/April 2006 (a) and November/December 2006 (b).
Error bars represent the standard error for the 60% trimmed means of each sample.

The second approach involved hourly moisture sampling to determine the elevated dead fuel's rate of response to changing atmospheric conditions. This was carried out on two separate days, 12 December 2006 and 20 March 2007. Five samples of elevated dead fine fuel moisture content of approximately 15-30 g (dry weight) were collected at hourly intervals from 08:00 to 18:00. Weather instruments underneath the gorse canopy recorded meteorological conditions throughout the day: temperature and relative humidity with an aspirated psychrometer (Sato SK-RHG No.7450) at the time of sampling and continually throughout the day with sensors (Environdata RH21 and TA10 series) at 1 m height, wind speed at ground level and 1 m using sonic anemometers (Gill Instruments Windsonic), and solar radiation at ground level (Apogee PYR-S silicon pyranometer). Sampling days were selected so that the dead fuels were neither in a wetting nor drying phase from recent precipitation and were only responding to changes in the surrounding atmospheric conditions. The two days had very different weather patterns. Conditions on 12 December 2006 included a rapid increase in temperature and wind speed (19.5°C and 7 km h^{-1} at 12:00 to 29.3°C and 21 km h^{-1} at 13:00) and decrease in relative humidity (74% at 12:00 to 22% at 13:00). These changes were associated with the arrival of a strong northwest wind late in the morning. In this region of New Zealand, these winds are associated with low relative humidities and high temperatures, from the foehn effect of warm and dry air pushing over the Southern Alps mountain ranges onto the Canterbury Plains (Sturman, 2008). Conditions on 20 March 2007 followed a more typical trend of a building sea breeze from late morning into the afternoon, with moderate temperatures (maximum 22.1°C) and relative humidity (minimum 34%) levels throughout the day. The maximum wind speed recorded in the open during the afternoon was 17 km h^{-1}. These days were selected since they represented the two main types of weather conditions experienced during the fire season in this region. Samples were processed in the same manner as the daily moisture samples. A summary of the 22 observations of fuel moisture and weather data is contained in Table 5.2. The 60% trimmed mean was taken to represent the moisture content of the samples collected for each hour, with the standard error determined as described previously. Error bars are also included in the time-series plots in Figures 5.6 and 5.7.

The stands from which fuel moisture samples were collected for the daily and hourly observations were all similar in age, height, structure and density. The area consisted of fairly even-aged gorse that was uniform across the site.

Table 5.2. Summary of fuel moisture and weather data for the days of hourly fuel moisture measurements, 12 December 2006 (n = 11) and 20 March 2007 (n = 11). Weather observations were taken at the onsite weather station in the open.

	Elevated *m* (%)		**Temp (°C)**		**Relative humidity (%)**		**Wind speed (km h^{-1})**		**FFMC**	
	Dec	Mar	Dec	Mar	Dec	Mar	Dec	Mar	Dec	Mar
Mean	14.0	18.7	22.5	18.0	49.3	64.7	19.2	9.4	83.5	78.5
Median	9.4	16.0	24.3	18.7	31.4	69.0	21.0	10.4	82.8	78.4
Max	26.4	27.9	30.0	22.1	96.3	98.0	44.9	17.1	90.2	81.5
Min	7.6	13.0	13.1	8.1	20.5	34.4	2.1	1.1	78.0	75.5

5.3.3. Moisture content predicted by the Fine Fuel Moisture Code

Actual *m* sampled in the field was compared against that predicted by the FFMC from the FWI System using data from the daily samples collected during March/April and November/December 2006. For each observation, the FFMC value corresponding to the hour of sample collection was determined. The hourly FFMC value was calculated as per Alexander *et al.* (1984), based on weather observations from the on-site weather station. Each of the hourly values of the FFMC were converted to moisture content, m_{FF}, using the standard FWI System conversion (Van Wagner, 1987):

$$m_{FF} = 147.27 \frac{(101 - F)}{(59.5 + F)}, \quad (5.4)$$

where F is the FFMC value. This scale for converting the FFMC value to an actual moisture content value is referred to as the FF-scale (Van Wagner, 1987).

The use of a revised form of the FFMC, the FX-scale, was proposed by Van Wagner (Lawson *et al.*, 1996) for use in countries with hot and dry climates. This provides a greater degree of drying at the lower end of the FFMC range. Hourly FFMC values were therefore also converted into moisture content, m_{FX}, using this FX-scale:

$$m_{FX} = 32.87 \frac{(101 - F)}{13.28 + F} \quad (5.5)$$

Plots of observed against predicted *m* using both the FF- and FX-scales to convert FFMC to moisture content are shown in Figure 5.3. Neither of these methods provided satisfactory predictions of *m*. The FF-scale (Figure 5.3a) significantly overpredicted *m* (R^2 of regression of observed values versus predictions = 0.68; mean error, ME = -11.81; root mean squared error, RMSE = 18.06). To assess the FFMC model's applicability to the data, a joint test was carried out on the regression parameter estimates of observed against predicted *m* to determine whether the intercept (α) and slope (β) of this regression line were significantly different from 0 and 1 respectively. This was carried out by means of a chi-square test of the increase in maximum likelihood from the restricted model, with $\alpha = 0$ and $\beta = 1$, using the R statistical software programme (R Development Core Team, 2008). Results showed that the intercept and slope were significantly different from 0 and 1 respectively (χ^2 = 123.56, d.f. = 2, $p < 10^{-8}$), indicating that the FFMC model was not applicable to the data.

The FFMC derived from the FX-scale (Figure 5.3b) was better than the FF-scale, but mostly underpredicted *m* (R^2 = 0.72, ME = 7.52, RMSE = 10.10). The joint test on the regression of observed against predicted *m* again showed that the intercept and slope were significantly different from 0 and 1 respectively (χ^2 = 35.33, d.f. = 2, $p < 10^{-7}$).

(a) (b)

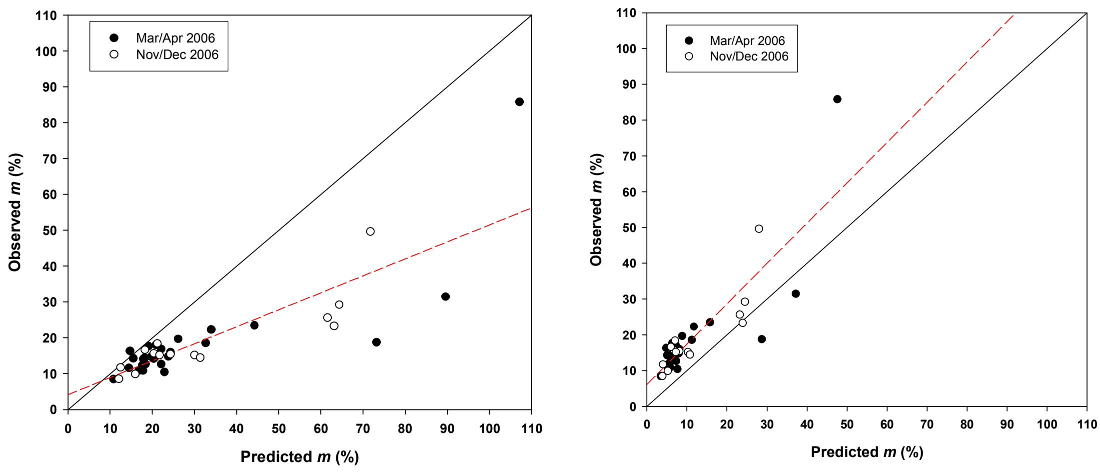


Figure 5.3. Observed against predicted values of *m* calculated from the FFMC using the FF-scale conversion (a) and the FX-scale (b).

In this and all similar plots that follow, the solid line represents the line of perfect agreement between observed and predicted, and the dashed line the regression of observed versus predicted values.

5.3.4. Regression models of Fine Fuel Moisture Code

To improve the predictive ability of the FFMC, regression models were developed, following the approach of Wotton and Beverly (2007). Data from the two periods of daily collection were used. Plots of actual m against m_{FF} and m_{FX} showed that variability increased with higher levels of m. The data were transformed using the natural logarithm to achieve homogeneity of variance, as in Wotton and Beverly (2007). Linear regressions of actual m against both m_{FF} and m_{FX} were carried out using the log transformed data.

A test dataset was created, using sampled m and the corresponding m (n = 18) from equations (5.4) and (5.5) for each observation. This dataset was obtained from fire experiments carried out at the study site during December 2006 and March 2007. For each of these experiments, five samples of m were collected from the experimental plots. These experiments were all carried out during the first half of each day (from around 09:00 to 13:00). The 60% trimmed means were determined from each of the five samples as previously described to provide a mean value of m for each sampling event. The gorse bushes that were sampled were similar in structure to those areas from where the daily and hourly samples were collected. Samples were mostly collected under different conditions to those from the model data. Conditions from early morning were usually cool and damp with little wind. The fuels then dried out as the morning progressed and wind speed increased. The range of values of m from this test dataset were mostly within the upper range observed from the daily sampling, with the lowest value at 14.6%. There were two observations at high m (126.7%, 105.9%). The test dataset therefore provided the opportunity for limited validation of these two regression models of m_{FF} and m_{FX}, as well as the bookkeeping model described later, beyond the original conditions in the model dataset.

The data used for these regression models were based on consecutive daily measurements of m at the same location (a repeated measures study). There was therefore the possibility of correlation between the errors in the consecutive measurements of m, as described in Gonzalez *et al.* (2009). To overcome this issue, an autoregressive model of order 1 was used for the error structure using the R statistical software programme (R Development Core Team, 2008). The autoregressive parameter was found to be non-significant in both cases. Ordinary regression models were therefore considered satisfactory. The model based on the conversion of the FFMC using the FF-scale was:

$$m = 1.9893(m_{FF})^{0.6545} \tag{5.6}$$

Comparing against actual values resulted in an R^2 of 0.64, ME = 0.79 and RMSE = 7.95.

The model based on the conversion of the FFMC to m using the FX-scale was:

$$m = 4.6381(m_{FX})^{0.5868}, \tag{5.7}$$

with an R^2 of 0.67, ME = 0.75 and RMSE = 7.65.

Equations (5.6) and (5.7) were used to calculate predicted *m* from the test dataset, and results are shown in Figure 5.4. The curves for *m* calculated from the FFMC using the FF- and FX-scales are also included. The two regression equations showed reasonable predictive power at higher values of FFMC, but performed poorly at lower values of FFMC (less than 50). The standard FFMC relationships did not fit the data well either. The FFMC relationship based on the FF-scale predicted two observations of high *m* and low FFMC very well. However, once the model data (used to derive regression equations (5.6) and (5.7)) were also plotted on Figure 5.4, it was apparent that prediction of *m* at these lower values of FFMC was still problematic.

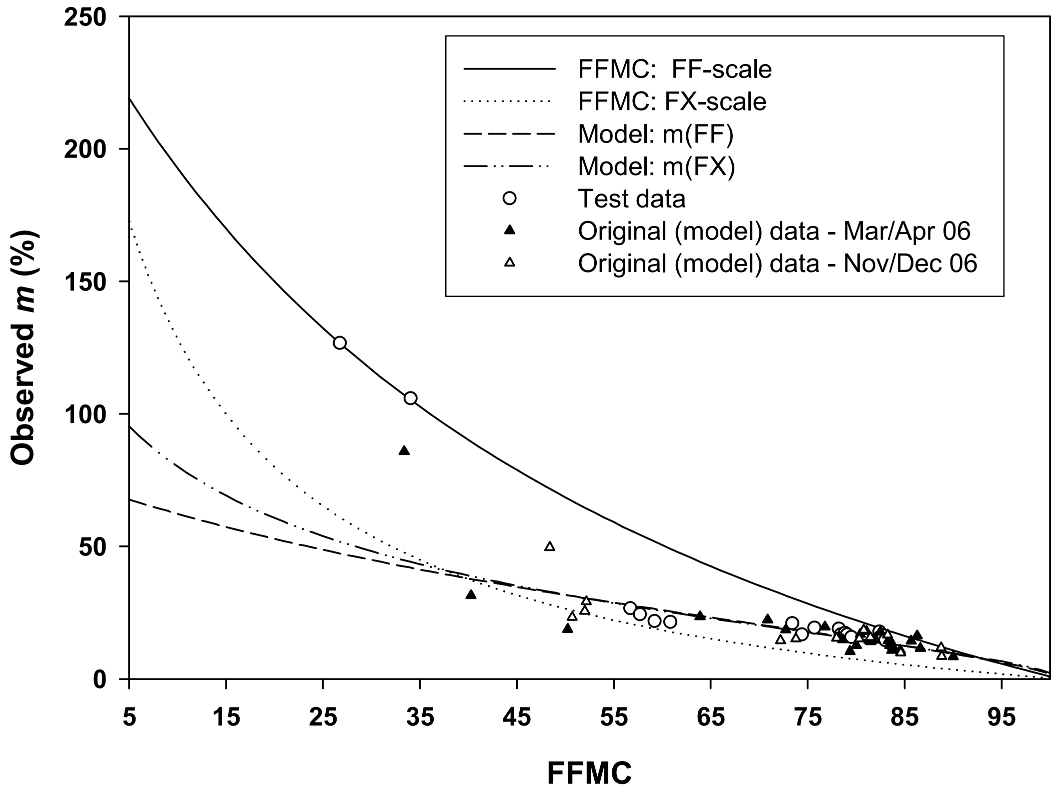


Figure 5.4. Comparison of observed *m* from the test dataset against the FFMC conversion using the FF- and FX-scales, as well as the regression models based on these conversions. Original data used to derive the regression models are also displayed for comparison.

5.3.5. Response time and EMC modelling

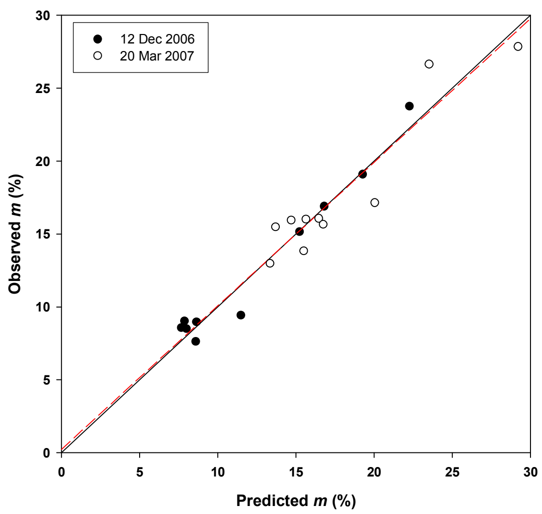
The method of Catchpole *et al.* (2001) was used to determine the response time (τ) and EMC of elevated dead fine fuels from field data of actual m. Data from the hourly fuel moisture measurements on 12 December 2006 and 20 March 2007 were used. Equation (5.2) was used to predict m, using equation (5.3) for EMC. A least squares approach was used to determine the values of τ, a and b which minimised the sum of squares of error (SSE) between observed and predicted m.

Equations (5.2) and (5.3) were applied to the field data, initially using the temperature and relative humidity recorded under the canopy with the aspirated psychrometer at the time of sampling. The previous hour's actual m was used for m_0 in equation (5.2), since the purpose was to determine τ and the EMC as well as possible. To initialise the equation to calculate values of q and m, starting values of a and b were determined from results of a study carried out in an environmental chamber (Pippen, 2007). This study used Australian heath and woodland fuels from the Sydney basin area. Whilst distinct from gorse fuels, this is the most recent work on EMC in shrub fuels and the values for the heathland fuels were deemed appropriate to initialise equation (5.2). The heathland (sedges and rushes) values for a (0.246) and b (-0.046) under adsorbing conditions were used to initiate calculations. To determine the values for a and b under desorbing conditions (a_d and b_d), the average of the differences between adsorption and desorption for all the values of a and b across the four fuel types tested by Pippen (2007) was used. This resulted in the value of a_d being equal to the value of a (adsorption) plus 0.0184, and the value of b_d equal to the value of b (adsorption) minus 0.0018. This approach was used to avoid minimising the SSE by solving for 5 parameters in such a small dataset. The SSE was minimised using the 'Solver' application in Microsoft Excel®.

For operational applications, weather data are only available from the network of standard meteorological stations across the country. These weather stations are located in open clearings, and analyses showed that fuel-level meteorological conditions were significantly different to those measured in the open at the onsite weather station. The response time and EMC were therefore also determined using observations of temperature and relative humidity recorded in the open from this weather station.

Using temperature and relative humidity under the canopy, a response time (τ) of 0.64 hours (approximately 38 minutes) was estimated, with associated values of *a* and *b* of 0.279 and -0.055 respectively. The plot of observed versus predicted *m* is shown in Figure 5.5(a). The model predicted the fuel moisture content very well ($R^2 = 0.94$, ME = -0.01, RMSE = 1.40).

(a)



(b)

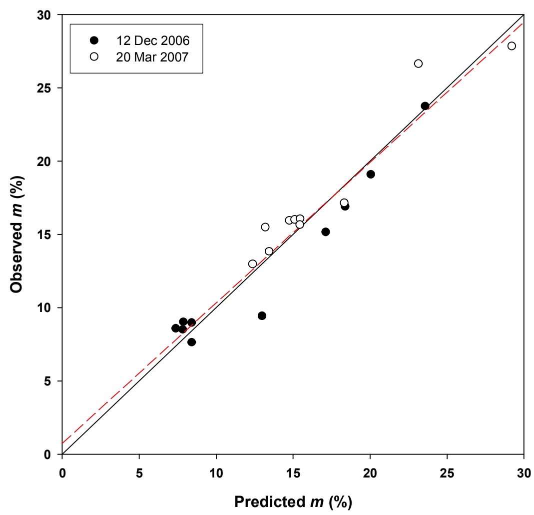


Figure 5.5. Observed against predicted *m* using the method of Catchpole *et al.* (2001), with temperature and relative humidity from an aspirated psychrometer under the canopy (a) and from a standard meteorological station in an open clearing (b).

Time-series plots of observed and predicted values of *m* for the two days' sampling are shown in Figures 5.6(a) and (b). Predicted values followed those observed from field sampling quite well. There was a general trend of slight underprediction of *m* during the mid- to late-afternoon on both days. However, there was slight overprediction during the later stages of the afternoon (17:00 and 18:00) on 20 March 2007. More significant over- and underprediction of *m* occurred during the morning of 20 March 2007. However, all of the errors were less than 3%, with the exception of one observation (3.11%).

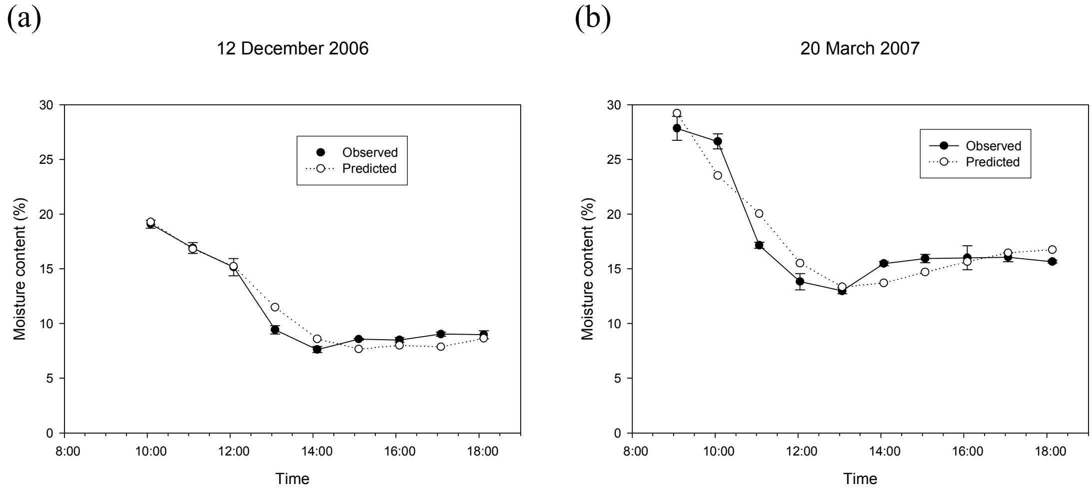
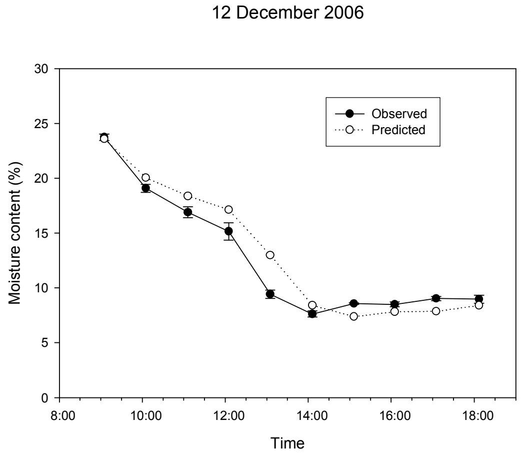


Figure 5.6. Time-series plots of observed and predicted *m* for 12 December (a) and 20 March 2007 (b) using the method of Catchpole *et al.* (2001), with temperature and relative humidity measured under the canopy.
Error bars represent the standard error for the 60% trimmed means of each sample.

The response time (τ) derived using data from the on-site weather station in the open was 1.29 hours (approximately 77 minutes), with corresponding values of *a* and *b* 0.279 and -0.055 respectively. The plot of observed versus predicted values is shown in Figure 5.5(b). The model again predicted *m* very well ($R^2 = 0.92$, ME = 0.11, RMSE = 1.54). Time-series plots of observed and predicted values for the two days' sampling are shown in Figures 5.7(a) and (b). Predicted values again followed observed values reasonably well, with slightly larger differences for some periods (especially during the afternoon periods) compared to when weather conditions under the canopy were used (Figures 5.6(a) and (b)). In this case, all of the errors were less than 4%, with most less than 2%.

(a) (b)



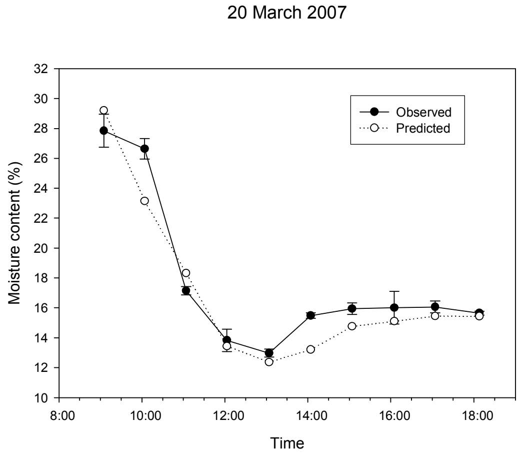


Figure 5.7. Time-series plots of observed and predicted m (a, c) and residuals (b, d), using the method of Catchpole *et al.* (2001), with temperature and relative humidity measured in the open.

Error bars represent the standard error for the 60% trimmed means of each sample.

5.3.6. Bookkeeping model of fuel moisture

The daily data collected from the two periods during 2006 were combined into a single dataset, with hourly readings from the on-site weather station. A calculation routine to predict m was created, based on a combination of the methods of Catchpole *et al.* (2001) and the FFMC (Van Wagner, 1987). Equation (5.2) was used to calculate m based on the previous hour's moisture content (m_0), fuel response time (τ) and EMC for the current (q) and previous (q_0) hours. For simplicity, τ only varied depending on whether the fuel was absorbing or desorbing.

This calculation routine assumes that if m_0 is below a threshold moisture level (m_t), then the fuel is responding only to changes in surrounding atmospheric moisture (not drying or wetting as a result of direct or surface moisture). This value of m_t was initially set at 35% (fibre saturation point). Under these conditions, m is calculated using equation (5.2). Where m_0 is greater than m_t, equation (5.2) is still used to calculate m, but τ is calculated from k_d, based on the hourly FFMC equations given in Alexander *et al.* (1984) and as shown below. Equation 5(a) from Alexander *et al.* (1984) is used to calculate m for the hourly FFMC routine under drying conditions:

$$m = E_d + (m_0 - E_d)e^{-2.303k_d}, \tag{5.8}$$

where:

$$k_d = 0.0579k_a e^{0.0365T}, \tag{5.9}$$

and T is air temperature (°C), and k_a is a function of relative humidity and wind speed (see equation (3b) in Alexander *et al.* (1984).

The uncentred piecewise solution to Byram's equation in the interval δt (see Catchpole *et al.* 2001) is:

$$m = q + (m_0 - q)e^{-\frac{\delta t}{\tau}} \tag{5.10}$$

For a period of δt = 1 hr, and with $q = E_d$ it can be seen from equation (5.8) that

$$e^{-2.303k_d} = e^{-\frac{1}{\tau}} \tag{5.11}$$

Solving for τ yields:

$$\tau = \frac{1}{2.303k_d} \tag{5.12}$$

It is then possible to calculate τ from k_d using equation (5.12), and this value of τ can then be used to calculate λ in the centred piecewise approximation in equation (5.2). This is then applied to calculate m for instances where m_0 is greater than m_t. Wetting of fuels by atmospheric humidity (adsorption) is accounted for using equation (5.2) up to the fibre saturation point of 35%; above this level the fuels are considered to be in a drying phase unless precipitation occurs (above the fibre saturation point, m_0 will always be greater than q_w *and* q_d). The addition of moisture following precipitation follows the procedure for the hourly FFMC outlined in Alexander *et al.* (1984).

Initially τ, a and b were set equal to the values found using the hourly data from the onsite weather station, but allowing them to vary gave a better fit to the daily data. This seemed reasonable, as the daily data were sampled over a wider range of conditions. The minimisation was carried out in a Microsoft Excel® spreadsheet, using the 'Solver' application to determine the values of the parameters (τ, a, b, m_t) that gave the best fit of the model to the data by minimising the value of the mean absolute error (MAE). The MAE was used instead of the SSE, since very high values of m following large rainfall events influenced the SSE strongly because the errors are squared. The model did not perform adequately during and following rainfall events. In particular, the fuels did not respond adequately to drying following rainfall events where there was a significant decrease in relative humidity in the hours following a rainfall event and leading up to sampling in the afternoon. To account for these different drying rates, an additional threshold condition was included. Where m_0 was greater than m_t and the relative humidity for the current hour was greater than or equal to the relative humidity threshold (h_t), equation (5.9) was used to determine k_d (Alexander *et al.*, 1984), and then to calculate the corresponding τ and λ values. Where m_0 was greater than m_t and the relative humidity for the current hour was less than h_t, equation (5.9) was used for k_d, but the constant of 0.0579 was changed to provide a better prediction of m. A rainfall threshold was specified, whereby rainfall amounts of 0.2 mm or less during the preceding hour were disregarded. This value was derived from field measurements that compared rainfall under the gorse canopy to that received in the open. Small amounts of rainfall were intercepted by the top (live) canopy layer and did not reach the elevated dead fuel layer. This was smaller than the threshold of 0.6 mm used by the FWI System for the surface layer in conifer forests (Van Wagner, 1987), but is reasonable for the elevated dead fuel layer in gorse. The elevated fuel layer would receive more precipitation than the surface layer, and the gorse canopy probably would intercept less rainfall since it is generally less dense than a mature conifer forest canopy. The effect of dew on fuel moisture was not accounted for, as the FFMC does not model the impact of dew on fine fuel moisture (Péch, 1991; Viney & Hatton, 1989). Published values of dew deposition in different fuels also indicated that the amounts of moisture likely to be received would be insignificant. Monteith and Unsworth (1990) state that the maximum rate of dew deposition on a clear night (in saturated air) is approximately 0.06 to 0.07 mm h^{-1}, and that maximum deposition is probably in the order of 0.2 to 0.4 mm per night. Other values for overnight dew deposition range from 0.13 mm on short grass (Monteith, 1957) to 0.61 mm on arid grasslands (Hicks, 1983). In the case of gorse, it is possible that dew deposited would be intercepted by the canopy, with very little moisture reaching the elevated dead fuel layer. Given that the rainfall threshold was specified at 0.2 mm and the low amounts of overnight dew deposition specified in the literature, moisture from dew deposition was disregarded. However, this is a topic that could require further investigation to clarify the role of dew on overnight levels of *m*.

Calculations were initialised using the field-derived response time ($\tau = 1.29$), h_t = 80%, m_t = 35% based on Cheney (1981), and with coefficients for equation (5.9) as specified in Alexander *et al.* (1984). Parameters that were adjusted to minimise the MAE were m_t, h_t, τ, a, b and the constant 0.0579 from equation (5.9) (for conditions where m_0 was greater than m_t and the relative humidity for the current hour was less than h_t). A summary of the resulting calculation routine is:

1. If $m_0 < 35\%$, use equation (5.2) to calculate *m*, with λ based on $\tau = 1.79$.
2. If $m_0 \geq 35\%$ and RH < 70%, use equation (5.2) to calculate *m*, but calculate λ based on τ derived from k_d (equation 5.12), using the coefficient for k_d as specified in equation (5.13).
3. If $m_0 \geq 35\%$ and RH ≥ 70%, use equation (5.2) to calculate *m*, but calculate λ based on τ derived from k_d, using the coefficient for k_d as specified in equation (5.9).
4. In all instances, precipitation amounts less than or equal to 0.2 mm received over the preceding hour are ignored. If precipitation exceeds 0.2 mm, then the rainfall effect is calculated as described in Alexander *et al.* (1984).

Values of *a* and *b* were 0.28 and -0.05 respectively. Adjusting the value of h_t to 70% and retaining m_t at 35% were found to be optimal. The revised equation for calculation of k_d as described in step 2 above was:

$$k_d = 0.1566 k_a e^{0.0365T} \qquad (5.13)$$

The model provided reasonably reliable predictive capability for *m* (R^2 = 0.87, ME = -0.72, RMSE = 4.87). Observed versus predicted values are shown in Figure 5.8(a). Three data points (marked with a cross in Figure 5.8) did not fit the model well, and this was particularly evident in the plot of residuals against predicted values (Figure 5.8(b)). In two instances, *m* was overpredicted: 29.2% actual versus 47.1% predicted (2.6 mm of rainfall received in the open in the preceding 9 hours), and 18.8% actual versus 38.8% predicted (6 mm of rainfall in the preceding 20 hours). In the case of the third observation, *m* was underpredicted: 49.6% actual versus 37.8% predicted (1.8 mm rainfall up to and including the hour of sampling).

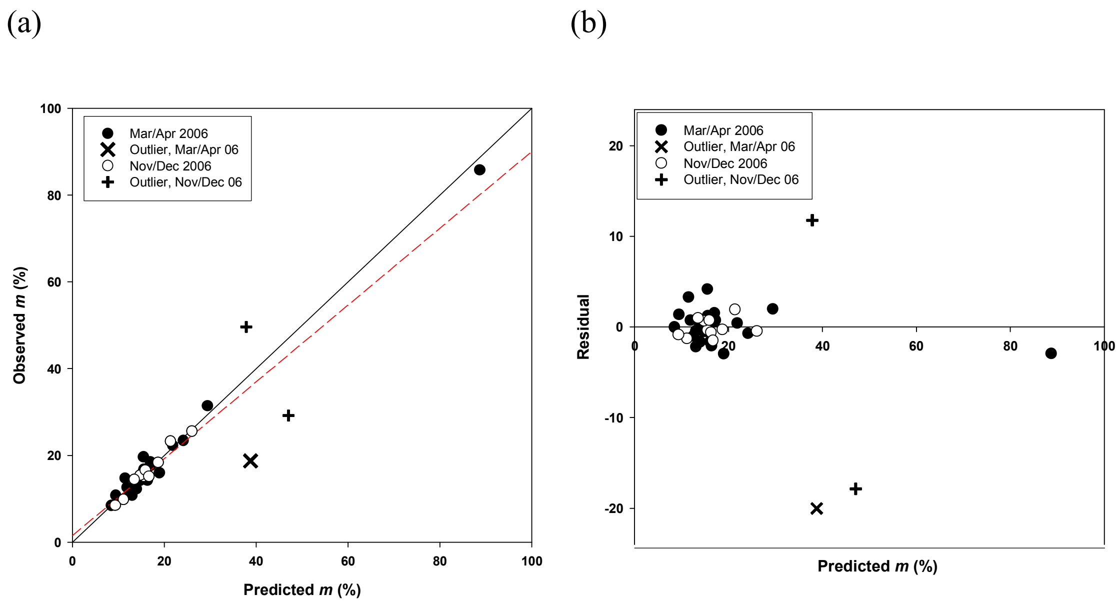


Figure 5.8. Observed against predicted *m* (a) and residuals versus predicted (b), derived from fitting the bookkeeping approach to field data. Outliers are marked with a cross.

The test dataset was used to test the bookkeeping routine, with hourly weather data and FFMC values incorporated (Figure 5.9). The model provided reliable predictions of *m* (R^2 = 0.95, ME = 2.77, RMSE = 7.15), apart from the two observations at high *m* which were significantly underpredicted (observed 105.87% and 126.72% versus predicted values of 83.38% and 111.31% respectively).

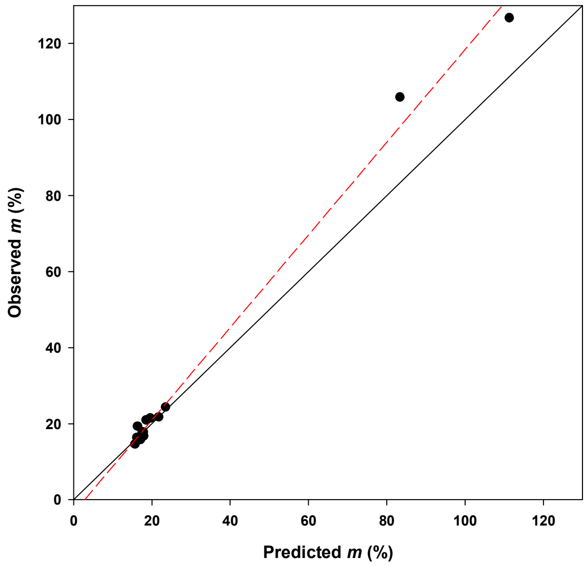


Figure 5.9. Observed versus predicted *m*, with predictions derived from applying the bookkeeping model to the test dataset.

The bookkeeping method involves three phases to predict *m*, with different values of response time (τ) for each phase. For values of *m* below 35%, τ was set to 1.79 hours. The average values of τ during each of the other two phases (dependant upon m_0 and RH) were determined to compare the different response times (and drying rates). For conditions where $m_0 \geq 35\%$ and RH < 70%, the average value of τ was 3.32 hours. Where $m_0 \geq 35\%$ and RH ≥ 70%, the average value of τ was 26.70 hours. The bookkeeping method therefore provided for the fastest response time (rapid fuel drying) at values of *m* below 35%, and then slowed drying for the other two phases (above *m* = 35%), markedly so for conditions where RH was greater than 70%.

5.4. *Discussion*

The performance of the different approaches to model *m* is compared in Table 5.3. The FFMC predicted *m* poorly, with overprediction from the FF-scale and underprediction from the FX-scale. Some overprediction of *m* from the FF-scale could be due to the restricted amplitude of the hourly FFMC curve during overnight periods without rain, as reported in Lawson and Armitage (2008). However, this is unlikely to have been the only cause of overprediction, since there were a number of rainfall events throughout both the March/April and November/December 2006 sampling periods.

Regression models using FFMC converted to moisture content with the FF- and FX-scales showed reasonable fits at FFMC values above 50, but when applied to the test dataset they did not perform well. They performed better with regard to ME, but the RMSE values were large (Table 5.3) because of two influential observations with low FFMC (high *m*), as shown in Figure 5.4. These poor results indicate that the underlying equations of the FFMC either require adjustment for response time and EMC, or are not applicable to elevated dead gorse fuels. This is perhaps not surprising, given that the FWI System is largely an empirical system based on a reference fuel type – forest floor fuels of conifer forests (Van Wagner, 1987). These gorse fuels are significantly different to this reference fuel type, mostly because of their elevated and more exposed arrangement. The hourly FFMC requires further validation to conditions beyond the fuel type, latitude and weather regimes under which it was developed (Beck & Armitage, 2004).

Table 5.3. Comparison of the different modelling approaches derived from the model dataset and applied to the test dataset. m_{FF} and m_{FX} refer to *m* from the FF- and FX-scales of the FFMC respectively.
In all cases, the models were significant with $p<0.0001$.

MODEL DATASET					
	m_{FF}	**m_{FX}**	**Regression m_{FF} (Eq. 5.6)**	**Regression m_{FX} (Eq. 5.7)**	**Bookkeeping model***
N	42	42	42	42	40
RMSE	18.06	10.10	7.95	7.65	4.87
ME	-11.81	7.52	0.79	0.75	-0.72
R^2	0.68	0.72	0.64	0.67	0.87

TEST DATASET					
	m_{FF}	**m_{FX}**	**Regression m_{FF} (Eq. 5.6)**	**Regression m_{FX} (Eq. 5.7)**	**Bookkeeping model***
N	18	18	18	18	15
RMSE	14.90	22.36	24.14	23.01	7.15
ME	-10.59	14.14	8.36	8.13	2.77
R^2	0.88	0.93	0.82	0.86	0.99

* *n* is lower for the bookkeeping model due to starting values for the model dataset being omitted (for the two daily periods, the starting values for the bookkeeping model were manually set to equal sampled *m*). In the case of the test dataset, *n* for the bookkeeping model was further reduced by samples being collected within the same hour.

Response times (τ) determined from the field data indicated that the elevated dead fuel layer responded to atmospheric moisture changes quickly – 38 minutes using temperature and relative humidity under the canopy (at fuel level), compared to 77 minutes (1.28 hours) using weather readings in the open. The reason for the different values of τ is due to the significant differences between weather conditions under the canopy and those in the open. A significant lag in fuel-level temperature and relative humidity behind that in the open was also observed. Trends in relative humidity under the canopy compared to those in the open for 20 March 2007 (Figure 5.10) suggest that the canopy shelters the fuel from changes in the open. Relative humidity under the canopy lagged behind that in the open during the morning. There were also likely to have been significant influences from transpiration within the canopy. For modelling purposes, it was more appropriate to use τ determined from weather conditions in the open (77 minutes), since weather observations for fire danger monitoring are all collected in the open. Furthermore, this value of τ was adequate when used in the models to predict *m*, based on a level of accuracy of 2%. Using the current rate of spread model for New Zealand shrub fuels (Anderson, 2009), it was found that fuel moisture prediction errors of the order of 2% resulted in differences in predicted rates of spread of up to 615 m h^{-1} when wind speeds were between 0 and 25 km h^{-1}. This corresponds to about 23% of the spread rate. Whilst this appears to be a large error, it is considerably smaller than the errors of up to 80% in predicted spread rate for errors of 2% in fuel moisture estimates using the Australian McArthur fire behaviour models (Trevitt, 1988). It is important for fire managers to understand the effects on rate of spread from minor changes in fuel moisture.

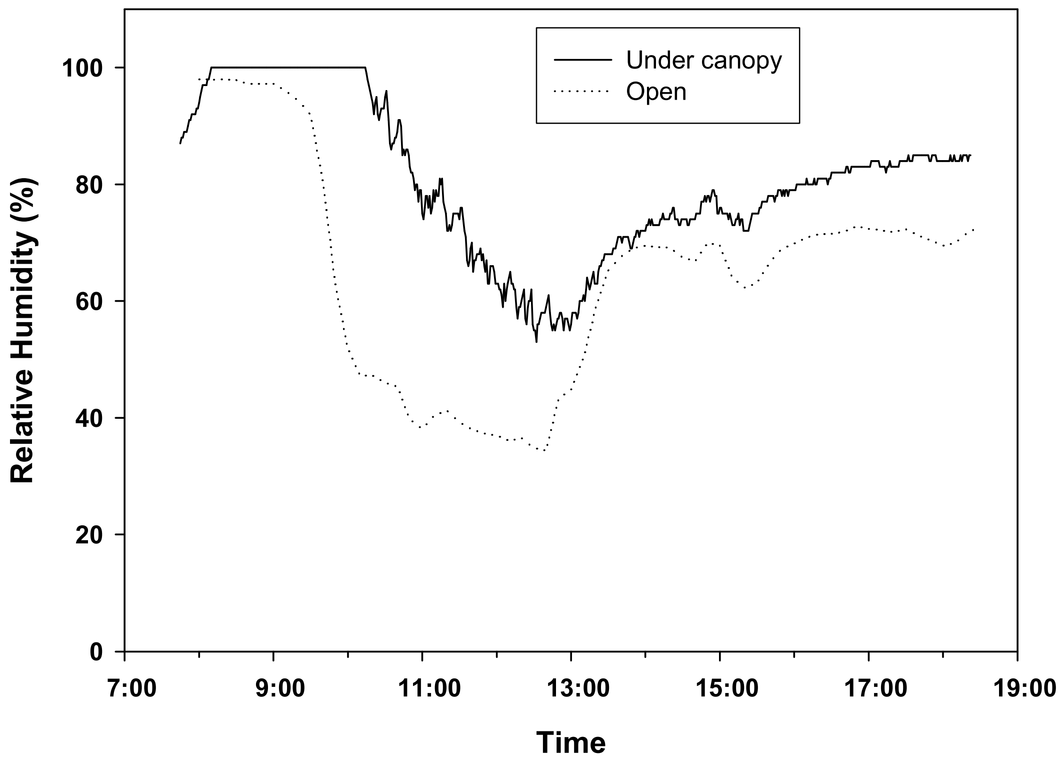


Figure 5.10. Relative humidity recorded under the canopy and in the open during hourly fuel moisture sampling on 20 March 2007.

Catchpole *et al.* (2001) determined values of τ of 3.84 hours for elevated mallee heath fuels in Western Australia and 1.92 hours for Tasmanian buttongrass moorland fuels, suggesting that the longer response time for the former was possibly due to waxes and oils in the leaves. Pippen (2007) determined a response time of 57 minutes for heathland (sedges and rushes) fuels from the Sydney basin area of eastern Australia. These are comparable to, although somewhat larger than, the response time in gorse of 38 minutes that was determined from the fuel temperature and humidity.

The bookkeeping model was the most reliable for both the model and test datasets (Table 5.3). In the three instances where predictions of m were particularly poor (Figure 5.8), the most likely explanation was the inability to model meteorological conditions under the canopy at fuel level. In all three cases, sampling followed a prior period of precipitation (usually during the preceding overnight period). It was likely that interception by the canopy allowed less precipitation to reach the elevated fuel layer than indicated by the rain gauge located in the open. Distribution of precipitation under the canopy was also observed to be highly variable. In the case of the third observation (m underpredicted), light drizzle was falling around the time of sample collection, so it is possible that some surface moisture was present on the sample. Relative humidity in the open decreased from 83% (previous hour) to 65% at the time of sample collection. Relative humidity under the canopy probably did not decrease to the same extent, thereby maintaining m at a higher level than that predicted by the model based on open weather conditions.

The promising results with the bookkeeping model indicate that modification of the FFMC to accommodate the different response times and drying rates of this fuel layer is appropriate. The underlying logic of this approach also appears sound, incorporating physical processes of moisture exchange with field-derived parameters for τ. This model is limited by the lack of adequate models of fuel-level temperature, relative humidity and wind speed. The challenge lies in developing models of fuel-level meteorology that use weather inputs from standard meteorological stations situated in the open. Improvements to the current techniques of interpolating weather observations from weather stations at single points across landscapes with complex terrain will also reduce further sources of error in operational systems. This is particularly the case for rainfall in New Zealand (Tait *et al.*, 2006).

The model is also limited in that it can only be applied with confidence to gorse fuels similar in structure to those at the study site, and under a range of weather and fuel moisture conditions similar to those contained in the model datasets. These datasets were limited in the range of m, with very few observations above 35%. This is because the original aim was to collect field data during the fire season under drier conditions where fuels were not generally influenced by rainfall. The model therefore requires further validation under a broader range of weather and fuel moisture conditions. Data were also collected from a single study site and, whilst broadly representative of mature gorse fuels across New Zealand, different stand characteristics (such as age, height and density) were not accounted for. Other factors such aspect and climatic zone were also not considered. Models with a stronger physical basis that model vapour exchange better (e.g., Matthews, 2006), could also provide more accurate predictions and applicability to a broader range of fuel types.

The current daily system of fire danger rating, with observations collected at noon to calculate FWI System outputs that reflect conditions later in the afternoon, is not appropriate for gorse fuels with their fast response times. Hourly calculation would provide more accurate fuel moisture predictions, although this relies on a national network of fire weather stations that collect data on an hourly basis. In New Zealand, the national fire danger monitoring system has an extensive network of such weather stations (http://nrfa.fire.org.nz). The system could therefore be modified to report fire danger conditions hourly for shrub fuels. In addition, the model could be incorporated into an existing system of hourly fire weather forecasting that is available to fire managers. Similar efforts to provide hourly forecasts of FWI System outputs have been described by Beck and Trevitt (1989) and Beck *et al.* (2002).

Further work should validate this model through more extensive field data collection, and extend it to other shrub fuels. From an operational fire management perspective in New Zealand, the bookkeeping model is a more favourable alternative to developing a completely new system that requires wholesale changes to the current system of rating fire danger in shrub fuels.

Table 5.4. Summary of symbols used in equations.

Symbol	Definition	Symbol	Definition
E_d	EMC under drying conditions	m_0	Fuel moisture content from the previous time period (%)
E_w	EMC under wetting conditions	m_t	Fuel moisture content threshold, for the bookkeeping model
F	The Fine Fuel Moisture Code (FFMC)	q	Equilibrium moisture content (EMC)
H	Relative humidity (fractional)	q_0	Previous hour's EMC
h_t	Relative humidity threshold, for the bookkeeping moisture model	R	Universal gas constant (1.987 units)
k_a	Intermediate step variable to determine log drying rate	RH	Relative humidity (%)
k_b	Intermediate step variable to determine log wetting rate	T	Temperature (K or °C)
k_d	Log drying rate	t	Time
k_w	Log wetting rate	δt	Time period that defines the interval for λ in Equation (5.2)
M	Molecular weight of water (18.0153 g Mol^{-1})	ΔG	Change in Gibbs free energy
m	Fuel moisture content (%)	λ	$\exp\left(-\delta t/(2\tau)\right)$
m_{FF}	Fuel moisture content from the FFMC, using the FF-scale (%)	τ	Fuel response time (h)
m_{FX}	Fuel moisture content from the FFMC, using the FX-scale (%)		

Chapter 6:
Ignition and fire spread thresholds[12]

6.1. Introduction

Gorse *(Ulex europaeus*) is an evergreen, leguminous shrub. It is prickly, with sharp spines growing in the axils of leaves (Hoshovsky, 1989; Zabkiewicz, 1975). It is fast-growing with a lifespan of approximately 30 years, has nitrogen-fixing bacteria in nodules on the roots, sprouts from the stem and roots if cut or burned, and produces vast amounts of seed that can remain viable for over 30 years in the soil (Tarayre *et al.*, 2007; Zabkiewicz, 1975). Its natural distribution is predominantly across central and western Europe, where fire plays an important role in these and other shrublands (Di Castri, 1981; Gimingham & Chapman, 1979). It has also spread and become a serious weed problem around the world, for example in Hawaii, Australia, Chile, Costa Rica, New Zealand and the Atlantic coastal areas of North America (Hoshovsky, 1989; Tarayre *et al.*, 2007; Zabkiewicz, 1975). In New Zealand, it covers approximately 700,000 ha (Blaschke *et al.*, 1981) – nearly 3% of the land area of the country.

Fires in gorse, like other shrub fuels, can often burn at very high rates of spread and extreme fire intensities under levels of fire danger that would not be considered extreme in other fuel types, such as forest and grass (Baeza *et al.*, 2002; De Luis *et al.*, 2004; Fernandes, 1998; Fogarty, 1996). In New Zealand, fires in shrub fuels (including gorse) account for around 40% of the total annual area burned (Anderson *et al.*, 2008). Gorse is characterised by large amounts of elevated dead fine fuels (particles with diameter less than 5 mm) suspended from branches within the canopy layer and large amounts of dead litter on the ground. Total fuel loads of 46-52 t ha^{-1} have been reported for *U.europaeus* shrublands in Spain (Vega *et al.*, 2005). Sampling in New Zealand found total fuel loads of 26-74 t ha^{-1} across a range of 58 sites with significant variability in fuel age, cover and climate zones. Elevated dead

[12] The work presented in this chapter has been resubmitted to the International Journal of Wildland Fire following peer review. It is largely unchanged from the submitted manuscript and therefore some repetition in the background information will be evident.

fine fuel loads represented on average 33% of the total available fuel load for each sample (Scion, unpubl. data). Elevated fuels are more flammable and carry fire easier than lower layers, such as surface litter, since they are more exposed and aerated and dry quicker. Gorse fuels also have a very narrow and defined threshold, below which fuels may ignite but do not spread (i.e., burn individual bushes or clumps), and above which ignitions rapidly develop into fast-spreading and very high-intensity fires. The ability to determine conditions under which ignition sources are likely to result in wildfires that spread and require suppression effort is critical for effective fire management. This information is also required to develop safe and effective prescriptions for controlled burning operations.

Fire danger rating in New Zealand is based on the Canadian Forest Fire Danger Rating System (Anderson, 2004; Stocks *et al.*, 1989). Difficulties in developing reliable fire danger and fire spread models for New Zealand shrub fuels are partly due to an inability to identify the threshold conditions for successful ignition and fire spread (Anderson, 2009; Fogarty *et al.*, 1998). Similar problems have been encountered in European shrub fuels (Fernandes, 2001; Fernandes, 1998). Studies have been undertaken to determine ignition thresholds for a variety of fuel types through small-scale laboratory studies and field ignition trials. Laboratory studies have the advantage over field trials of providing controlled conditions and reduced costs and risks. However, field ignition trials allow the variability and complexity of 'real world' conditions to be incorporated into model development (Beverly & Wotton, 2007). Studies have focussed on ignition or fire spread thresholds in grass fuels (e.g., de Groot *et al.*, 2005; Manzello *et al.*, 2006; Stockstad, 1976) and the surface/litter layers in forests (e.g., Lawson *et al.*, 1994; Lin, 1999; Stockstad, 1975; Tanskanen *et al.*, 2005), including logging slash (Blackmarr, 1972). The Canadian Forest Fire Weather Index (FWI) System is in part based on extensive small-scale test fires conducted in the field in surface fuels across Canada between 1940 and 1961. Models that predict the probability of sustained flaming in forest and grass fuels were developed by Beverly and Wotton (2007) using this historic test fire dataset.

Some studies have been carried out to determine ignition thresholds in shrub fuels. Guijarro *et al.* (2002) did laboratory ignition tests and found that crushed *U.europaeus* litter had one of the highest ignition frequencies, rate of spread and combustion of the fuels tested. Plucinski and Anderson (2008) conducted laboratory studies of ignition thresholds in the litter layer of Australian shrub fuels. Dead fuel moisture content was the most important determinant of ignition success, along with species, type of ignition source and wind speed. Field experiments were recommended to complement the laboratory results.

Weise *et al.* (2005) and Zhou *et al.* (2005; , 2007; , 2005) conducted experiments in the laboratory using four common chaparral shrub species to model conditions for marginal burning in these fuels. They investigated the roles of slope, fuel load and arrangement, live fuel moisture content, air temperature, relative humidity and wind speed on fire spread thresholds. Models based on logistic regression (Weise *et al.*, 2005; Zhou *et al.*, 2007; Zhou, Weise *et al.*, 2005) and numerical modelling (Zhou, Mahalingam *et al.*, 2005) approaches included from four to six predictor variables, with live fuel moisture content, slope and a measure of the fuel properties (either load or arrangement) common to all four models. Weise *et al.* (2005) and Zhou *et al.* (2007) also found differences between the four species that were tested. However, Fletcher *et al.* (2007) found that live fuel moisture content had almost no influence on time to ignition and ignition temperature in Californian chaparral and Utah shrub fuels. Further work explored the effect of crown fuel bulk density on crown fire initiation from surface fires (Tachajapong *et al.*, 2008).

Small-scale experiments have been carried out in the field in some shrub communities. Early work by Bruner and Klebenow (1979) in pinyon-juniper communities (comprising *Pinus monophylla* and *Juniperus osteosperma*) of Nevada linked spread success to air temperature, wind speed and vegetation cover. More recently, Fernandes *et al.* (2008) determined thresholds for sustainability of surface fires in *P.pinaster* stands in northern Portugal with an understorey of *U.minor*, and found the moisture content of fine dead fuels to be highly significant. Research into fire behaviour in Calluna-dominated heathlands in Scotland found that the moisture content of both live and dead fine fuels was important for ignition and development of self-sustaining fires (Davies & Legg, 2008; Davies *et al.*, 2006). Pellizzaro *et al.* (2007) focussed on modelling ignitability or fire spread success based on annual variations in live fuel moisture content in Mediterranean shrub fuels, and also found differences in ignitability between shrub species.

Larger-scale field experiments have been carried out in Australia in the last two decades. In Eucalypt mallee vegetation with a heath understorey, McCaw (McCaw *et al.*, 1995) found that the moisture content of the surface litter was the most critical variable that determined fire propagation. Recent studies in Australia modelled fire spread success in similar mallee-heath fuels using wind speed, fuel characteristics and the moisture content of the near-surface fuel layer (Cruz & Gould, 2008). Near-surface fuels are a layer up to 1 m above the litter comprising low shrubs, grasses and suspended leaf, twig and bark material from the overstorey (Gould, McCaw, Cheney, Ellis, Knight *et al.*, 2007; Gould, McCaw, Cheney, Ellis, & Matthews, 2007). A near-surface fuel layer was also described in Tasmanian buttongrass moorlands, at heights from 15-50 cm. The moisture content of this layer was important in determining thresholds at which fires would self-extinguish (Marsden-Smedley *et al.*, 2001).

The objective of the work presented in this paper was to determine the variables that affected ignition and sustained fire spread in gorse, and to develop a model using these variables to predict threshold conditions for ignition and fire spread. The work on sustainability of ignition was carried out in the field on a scale that was representative of prescribed burning.

6.2. Methods

6.2.1. Ignition experiments

Ignition experiments took place at a location in the Waimakariri River (43°22′S, 172°04′E), approximately 50 km WNW of the city of Christchurch in the South Island of New Zealand (Figure 6.1). This is a wide, braided river bed, and the study site was located in area prone only to occasional flooding during very heavy rainfall events. The area consisted of numerous clumps of gorse bushes scattered across the river bed. There was a mostly stony and boulder cover, with silt-loam sands underneath of soil type Selwyn-Waimakariri (New Zealand Soil Bureau, 1968). The purpose of these experiments was to determine the threshold conditions for successful ignition in gorse. Experiments were carried out on 13 April, 10 May (autumn) and 8 November 2006 (spring).

Figure 6.1. Ignition experiments carried out at the Waimakariri site on 13 April 2006.

Ignition experiments commenced under conditions that were believed to be marginal for successful ignition, usually cool and damp with little wind and high fuel moisture. Successive ignition tests were carried out from early morning until the middle of the day (under drying and increasingly windier conditions) until the fuels were observed to ignite easily. A portable weather station was erected onsite to record temperature (°C), relative humidity (%) and wind speed (km h^{-1}) at 2 m above the ground. Hourly values of the Fine Fuel Moisture Code (FFMC), Initial Spread Index (ISI) and Fire Weather Index (FWI) of the FWI System were calculated from these weather data, using the methods described in Alexander *et al.* (1984). These calculations were initiated using values of FFMC, Duff Moisture Code (DMC) and Drought Code (DC) from the nearest national fire weather network weather station (located at Darfield, approximately 15 km southeast of the experimental site). Wind speed measured at a height of 2 m was multiplied by 1.48 to approximate the wind speed at a height of 10 m, as described in Turner and Lawson (1978). The 10 m wind speed is required for the FWI System, and also aligns with the standard meteorological measurement of wind speed. Five samples of fuel moisture were taken prior to ignition from each of the fuel layers present: near-surface dead (elevated dead gorse needles and small twigs < 5 mm diameter up to approximately 30 cm above ground level); elevated dead (elevated dead gorse needles and small twigs < 5 mm diameter from 30 cm above ground level to underneath the green canopy layer) and live (green foliage < 3 mm diameter collected from the live canopy fuels). Surface (litter) fuels and duff were not present at the Waimakariri site, due to the nature of the site as previously described.

The elevated dead fine fuel layer was ignited at a height of approximately 0.5 m above ground level. This is the usual height for ignition in this fuel layer during prescribed burning operations (and probably arson fires). The ignition experiments carried out on 13 April 2006 alternated between use of a drip torch containing a kerosene/diesel mix (50:50) and a standard cigarette lighter. The lighter was found to be successful without the need for the additional heat and flame output from the drip torch in these small clumps, and subsequent experiments used only a lighter for ignition. Data analysis excluded observations where the drip torch was used for ignition, to eliminate any possible enhanced ignition effect from the additional accelerant provided by the drip torch. For each experiment, the lighter was positioned such that the pilot flame was in contact with the elevated dead fuel and held there either until ignition occurred, or it was obvious that ignition would not succeed. Ignition experiments were classed as failure, marginal or success. A successful ignition occurred when it was clear that flames had developed and spread to the top of the gorse clump and were burning the clump completely. Marginal were those ignitions where the initial ignition appeared to be successful, but the fire subsequently self-extinguished without burning through the gorse clump. A failure was recorded when an ignition either completely failed to establish, or when individual gorse needles or twigs burned or smouldered from the pilot ignition source before self-extinguishing and failing to develop into a fire.

The ignition experiments carried out on 13 April and 10 May 2006 were successful ignitions in all cases except one (which was classed as a marginal ignition). It became clear from these experiments that gorse fuels ignited in all but the dampest of conditions. To determine the threshold conditions where ignition attempts would change from being classed as either failure or marginal to success, the last set of experiments (8 November 2006) were carried out in the morning following a period of overnight rainfall. Fuels were saturated from this overnight rainfall (22.2 mm in the 24-hour period up to 08:00 on the 8th) and contained surface moisture at the time of the first trial (08:47). During the course of the morning, the fuels started to dry under the influence of solar radiation and steadily increasing winds until successful ignitions were recorded around 12:40. A summary of the fuel moisture and weather conditions from the ignition experiments is contained in Table 6.1. Weather conditions represent the conditions recorded at the time of ignition using the onsite portable weather station.

6.2.2. Fire spread initiation experiments

The ignition experiments showed that gorse fuels ignited easily under most conditions, apart from instances where fuels were saturated from precipitation. It was also apparent that, whilst these fuels ignited readily, the resultant fire did not always develop into a spreading fire. Conditions that drove fire spread therefore differed from those determining ignition successes. The study was therefore extended to determine the threshold conditions for fire spread.

These experiments were carried out near Pines Beach, a small community approximately 20 km north of Christchurch (43°21′S, 172°41′E). The site was located on privately-owned land in close proximity to the coast (approximately 1.5 km to the east). Vegetation consisted mostly of large areas of gorse vegetation, ranging from small clumps of a few metres in diameter to large continuous areas of mature gorse, and pasture grasses. Most of the gorse areas consisted of mature plants, with average heights ranging from 1.5 m to 2.5 m. The land was adjacent to other farming land and a plantation of *P.radiata*. The topography of the area is uniformly flat, with soils described as Yellow-brown Sands, comprising coastal sand and gravel with little or no topsoil differentiation (New Zealand Soil Bureau, 1968).

Areas of gorse were selected that could be ignited and would provide a short run to determine whether the experimental fire was likely to develop into a fire that would spread under the prevailing conditions. Plots were selected that aligned with the prevailing wind directions (mainly east-west). The plots were wider than 5 m, to allow an ignition line of at least 5 m to be lit without having to light to the edges (flanks) of the plot (to avoid edge effects). Plot lengths ranged from 8 m to 24 m (average 15 m) and plot breadth from 7 m to 15 m (average 11.5 m). Experiments were carried out over five days (14 & 15 December 2006 in summer; and 15, 16 and 22 March 2007 in autumn), with days selected where fires would be unlikely to spread during the initial experiments early in the morning, but spread easily later in the day once fuels had dried and weather conditions were conducive to fire spread (increased wind speed and temperature, decreased relative humidity). The days of the experiments usually followed rainfall events or periods of benign fire weather (high fuel moisture, low wind speed and low temperatures).

Plots were marked along their length with steel posts at 2 m intervals. Average fuel height was measured for each 2 m interval and also averaged over the length of the plot. Fuel height across all plots ranged from 1.4 m to 2.4 m (average 1.9 m), with the lower heights generally at the ends of plots (most likely a combination of edge effects and animal browsing). The steel posts served as reference points to record fire spread times and flame height and length. Experiments usually began between approximately 09:00 and 09:30 and continued through the morning until it was clear that fires were spreading easily (usually by 12:30). Prior to ignition in each plot, five fuel moisture samples were collected from each of the fuel layers present: duff (the loosely compacted and decomposing organic layer immediately below the surface litter layer and above the mineral soil layer – usually up to 50 mm depth); surface (the top 10 mm of the litter layer, including dead gorse needles and small twigs <5 mm diameter); near-surface; elevated dead; and live fuels (as described previously). Plots were ignited along the upwind edge and fire spread time was recorded along with general observations of fire behaviour (flame length and height, smoke colour and dispersion, etc.). Experiments were classed as failure, marginal or success. Failure was recorded where a plot was ignited but clearly failed to form a head fire and either spread intermittently (disjointed fingers of fire) for a short distance, or failed to spread at all, before self-extinguishing. Marginal spread was recorded where the fire initially seemed to develop, but failed to form a connected fire front and did not spread along the entire length of the plot and eventually self-extinguished (Figure 6.2a). A success was the result of the ignition line quite clearly developing into a spreading and connected fire-front that burned to the end of the plot and would easily have continued spreading were continuous fuels present beyond the end of the plot (Figure 6.2b).

Weather conditions were measured onsite from a weather station situated in an open clearing that recorded temperature (°C), relative humidity (%) and average wind speed (km h^{-1} at 10 m above ground) at 10-minute intervals, and hourly rainfall (mm). Weather readings from this station were used to calculate hourly values of the FWI System during the experiments, following the equations and approach as described in Alexander *et al.* (1984). The FWI System calculations were initiated with starting values of FWI System fuel moisture codes from a permanent fire weather station located nearby (Bottle Lake, approximately 12 km south of the study site). All weather data were averaged over the duration of each experiment. A summary of weather, FWI System and fuel moisture data from the experiments is contained in Table 6.2.

Additional measurements of wind speed were also collected during the fire experiments using a sonic and cup anemometer at 1.5 m and 2 m above the ground respectively (Sections 4.2 and 4.5). These anemometers were located in clearings between gorse clumps and at a suitable distance from the experimental plots so as to avoid any fire-induced effects. For observations at 2 m, wind speed was recorded at 1-minute intervals and then averaged over the duration of each fire experiment. However, data were only available for three of the five days of fire experiments (14 and 15 December 2006, 15 March 2007) due to a failure of the portable weather station datalogger on the remaining days. Wind speed observations at 1.5 m were measured every 5 seconds, and also averaged over the duration of each fire experiment.

(a)

(b)

Figure 6.2. Fire spread experiments carried out at the Pines Beach site, showing marginal fire spread (a) on 16 March 2007, and successful fire spread (b) on 15 December 2006.

Table 6.1. Summary of weather (including FFMC, ISI and FWI from the FWI System) and fuel moisture content (*m*) data recorded for the ignition experiments (n = 37).

	Elevated *m* (%)	**Near-surface *m* (%)**	**Live *m* (%)**	**Temp (°C)**	**Relative Humidity (%)**	**10 m wind (km h^{-1})***	**FFMC**	**ISI**	**FWI**
Mean (std error)	40.2 (4.7)	58.1 (6.1)	191.9 (6.5)	13.5 (0.4)	62 (2.7)	16.9 (1.7)	37.4 (5.9)	1.1 (0.3)	2.2 (0.6)
Maximum	98.9	107.4	252.8	18.0	83	37.2	84.4	5.2	11.1
Minimum	9.9	10.2	145.2	9.8	43	2.6	3.6	0.0	0.0

* Wind speed at 10 m height above ground.

Table 6.2. Summary of weather (including FFMC, ISI and FWI from the Fire Weather Index System) and fuel moisture content (*m*) data recorded for the fire spread experiments (n = 19).

	Duff *m* (%)	**Surface *m* (%)**	**Near-surface *m* (%)**	**Elevated *m* (%)**	**Live *m* (%)**	**Temperature (°C)**	**Relative Humidity (%)**	**10 m wind (km h^{-1})***	**FFMC**	**ISI**	**FWI**
Mean (std error)	133.6 (9.0)	114.2 (12.4)	67.4 (13.8)	33.7 (8.2)	206.8 (5.5)	14.6 (0.4)	69 (2.8)	10.2 (1.0)	67.3 (4.2)	1.4 (0.2)	3.0 (0.6)
Maximum	194.5	198.9	218.4	126.7	260.3	17.1	88	19.4	83.0	3.5	7.4
Minimum	60.5	22.7	18.2	14.6	174.7	10.8	37	2.9	26.8	0.0	0.0

* Wind speed measured at 10 m height above ground.

6.2.3. Data analysis

Probability of ignition success was modelled using ordinal logistic regression by fitting a proportional odds model, with the outcome of experiments classified as failure (0), marginal (0.5) or success (1):

$$P(I_s) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 x_1 + \ldots + \beta_n x_n)}}, \qquad (6.1)$$

$$P(I_{SM}) = \frac{1}{1 + e^{-(\beta_0' + \beta_1 x_1 + \ldots + \beta_n x_n)}}, \qquad (6.2)$$

where $P(I_S)$ is the probability of successful ignition, $P(I_{SM})$ is the probability of either successful or marginal ignition, $x_1, \ldots, x_n$ are predictor variables, and $\beta_0, \beta_0', \beta_1, \ldots, \beta_n$ are regression coefficients. Probability of fire spread success was modelled in the same manner, with *I* replaced by *F* in equations (6.1) and (6.2). Regressions were carried out in SAS using the 'PROC LOGISTIC' procedure (SAS Institute, 2004). To determine the variables that provided the best model fit, logistic regression was carried out using each of the fuel moistures (duff, surface, near-surface, elevated, live), weather (temperature, relative humidity, wind speed), relevant FWI System codes and indices (FFMC, ISI, FWI) and fuel height (for the fire spread data). In the case of the Waimakariri ignition dataset, only near-surface and elevated fuel moisture observations were available (surface and duff layers were not present at this site). Model building was done using stepwise procedures using the likelihood ratio χ^2 test (Hosmer & Lemeshow, 2000). Comparison between models was based on the values of the Akaike Information Criterion (AIC) and Schwarz Criterion (SC) (SAS Institute, 2004; Schwarz, 1978). Assessment of model goodness-of-fit and predictive power were based on the deviance goodness-of-fit test and the *c*-statistic, indicating the percent of cases where the model assigns higher probabilities to correct cases than incorrect cases (Garson, 2008).

6.3. *Results*

6.3.1. Ignition thresholds

Several of the independent variables used were correlated (see Table 6.3). Multicollinearity could not be avoided, in particular because the moisture contents and weather indices were naturally correlated. In addition, as the fuel dried out during the morning the wind tended to increase. This was a problem with models with more than one predictor variable, as, if one variable was included then the correlated variable tended not to be included.

Table 6.3. Pearson correlation coefficients (r) for fuel moisture and weather variables during the ignition experiments (n = 37).

	Elevated *m* (%)	**Near-surface *m* (%)**	**FFMC**
Temperature (°C)	-0.79***	-0.66***	0.62***
Relative humidity (%)	0.71***	0.52***	-0.43**
10 m wind (km h^{-1})[A]	-0.39*	-0.01	-0.08

* Significant at 5% level
** Significant at 1% level
*** Significant at 0.1% level
[A] Correlation coefficients were the same for 10 m and 2 m wind (10 m was calculated from 2 m values)

The measures of model fit and predictive power for single predictor variables are provided in Table 6.4. As for Table 6.3, only 10 m wind is displayed since the values of the model statistics were exactly the same for 2 m and 10 m wind values, This was because 10 m wind speed was calculated from the 2 m wind speed using a linear conversion of 1.48 (refer to Section 6.2.1). Elevated and near-surface moisture content, FFMC and ISI (but not wind) were all significant ($\alpha < 0.05$) for the likelihood ratio χ^2 test and non-significant for the deviance goodness-of-fit , but the best single-variable model was based on elevated dead fine fuel moisture content, *m*. A score χ^2 test indicated that the proportional odds model was appropriate ($\chi^2 = 1.12$, $p = 0.2899$). A logistic model including near-surface moisture content and relative humidity provided a slightly better fit (likelihood ratio $\chi^2 = 57.70$ ($p < 0.0001$); AIC = 23.96; SC = 30.41, deviance goodness-of-fit = 6.60 ($p = 1.00$); c-statistic = 0.986). However, this model was discounted since it only provided a marginally better fit than the single-variable model using *m*, there was high correlation between near-surface moisture content and relative humidity ($r = 0.52$, $p = 0.0010$), and because during field experiments it was obvious that the elevated layer was driving ignition success or failure, not the near-surface layer. None of the FWI System outputs were found to be significant variables for model inclusion.

The probability of ignition success, $P(I_S)$ was therefore given as:

$$P(I_S) = \frac{1}{1 + e^{-(14.7652 - 0.4950m)}}, \tag{6.3}$$

where *m* was the elevated dead fine fuel moisture content. The probability of ignition being successful or marginal, $P(I_{SM})$ was:

$$P(I_{SM}) = \frac{1}{1 + e^{-(17.6274 - 0.4950m)}} \tag{6.4}$$

From a fire management perspective, it is critical to know the actual levels of *m* that define the thresholds for ignitions being failure, marginal or success. To determine these threshold values a probability of 0.5 was used to determine the cut-off, and equations (6.3) and (6.4) were solved for *m* when $P(I_S) = 0.5$, and $P(I_{SM}) = 0.5$. This provided the threshold value for *m* that defined the boundary between failure or marginal for ignitions as 36%, and the threshold between marginal and success as 30%. Therefore, at values of *m* above 36%, ignitions would be predicted to be unsuccessful, for values of *m* from 30% to 36% ignitions would be predicted to be marginal, and at values of *m* below 30% all ignitions would be predicted to be successful. The plot of the observations from the ignition experiments, probability curves and boundaries for success/marginal and marginal/failure is displayed in Figure 6.3. Most of the observations were classified correctly (89%).

Table 6.4. Model statistics for the analysis of the ignition data, indicating suitability of models based on elevated *m*, near-surface *m* and FFMC. *p*-values are given in parentheses, where relevant ($n = 37$).
Non-significance for the deviance goodness-of-fit test indicates a good fit for the model, whilst significance for the likelihood ratio χ^2 test indicates good explanatory power in the model.

	Elevated *m* (%)	**Near-surface *m* (%)**	**FFMC**	**ISI**	**10 m wind (km h^{-1})**
Likelihood ratio χ^2	55.39 (<0.0001)	42.45 (<0.0001)	37.08 (<0.0001)	30.01 (<0.0001)	1.87 (0.1713)
Akaike Information Criterion (AIC)	24.27	37.22	42.59	49.66	77.80
Schwarz Criterion (SC)	29.11	42.05	47.42	54.49	82.63
Deviance goodness-of-fit	7.86 (0.9999)	20.81 (0.7952)	26.18 (0.7128)	33.25 (0.3581)	65.20 (0.0260)
c statistic	0.982	0.982	0.981	0.839	0.605

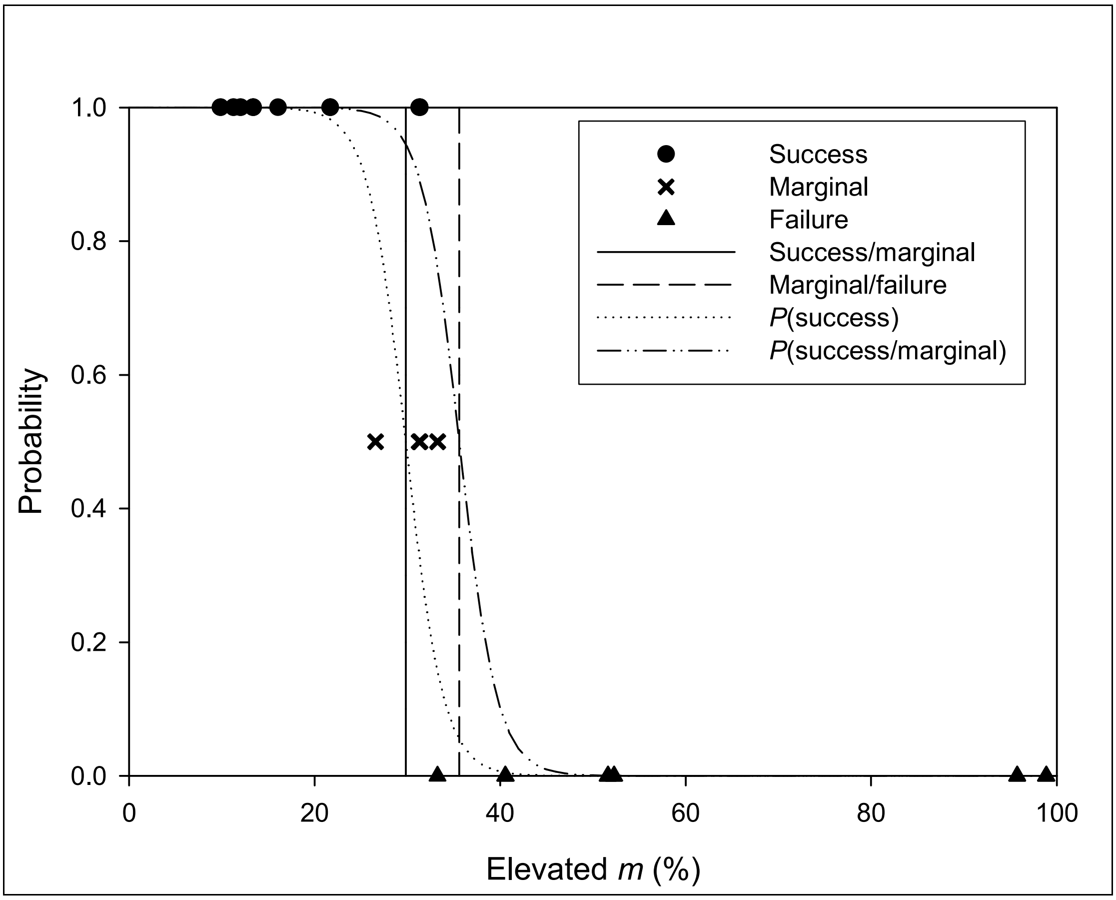


Figure 6.3. Plot of ignition data (categorised into success, marginal or failure), with the probability plots from Equations (6.3) and (6.4), and the lines demarcating the success/marginal and marginal/failure boundaries.

6.3.2. Fire spread thresholds

Fuel moisture variables used for the fire spread data were found to be strongly correlated with relative humidity, and to a lesser extent with temperature and wind speed (Table 6.5). Relative humidity was negatively correlated with fuel moisture, in contrast to the positive correlations found for the ignition experiments (Table 6.3). It would be expected that these correlations should be positive instead of negative, since an increase in relative humidity should increase the moisture content of the fine dead fuels. However, in this case the correlations were strongly influenced by three observations of very high moisture content (105.9% to 126.7%). These observations were from experiments carried out on the same day, following a period of significant rainfall the previous day that saturated the fuels. On the morning of the experiments the weather had cleared and was sunny and dry, with decreasing relative humidity through the morning (67% when experiments commenced at 11:00 to 37% by 12:30 for the last experiment). The moisture content of the fuels did not change as rapidly as the relative humidity, due to the high degree of fuel saturation, the time lag of the fuels in responding to atmospheric conditions, and significant differences that have been observed in relative humidity conditions under the gorse canopy (fuel-level) compared to those in the open where weather readings were collected (Anderson & Anderson, in press).

Table 6.5. Pearson correlation coefficients (r) for fuel moisture and weather variables during the fire spread experiments (n = 19).

	Elevated *m* (%)	Near-surface *m* (%)	FFMC
Temperature (°C)	0.18	0.21	0.06
Relative humidity (%)	-0.67**	-0.62**	0.53*
10 m wind (km h^{-1})	-0.21	-0.21	0.32
2 m wind (km h^{-1})	-0.23	-0.37	0.47
1.5 m wind (km h^{-1})	-0.40	-0.41	0.46*

* Significant at 5% level
** Significant at 1% level
*** Significant at 0.1% level

Measures of model fit and predictive power for single predictor variables are provided in Table 6.6. The best single-variable model was again based on elevated dead fine fuel moisture content, m. The score χ^2 test indicated that the proportional odds model was appropriate ($\chi^2 = 2.94$, $p = 0.0864$). None of the models with two predictor variables (moisture content and a weather variable) provided better fit. A model using ISI fitted the data almost as well as the model using m (Table 6.6). Such a model would have the advantage of incorporating both wind speed and m, since one would expect that wind speed should play a role in determining fire spread success. However, this model was discounted since there was a slight correlation between wind speed and m (Table 6.5) which confounded the roles of wind speed and moisture content in the ISI. In addition, separate work in these fuels has shown that the FFMC (which is a component of the ISI along with wind speed) is unsuitable for prediction of elevated dead fuel moisture content in gorse (Anderson & Anderson, in press). The probability of fire spread success, $P(F_S)$ was thus given by:

$$P(F_S) = \frac{1}{1 + e^{-(20.6059 - 1.0608m)}}, \qquad (6.5)$$

with m the elevated dead fine fuel moisture content. The probability of successful or marginal fire spread, $P(F_{SM})$ was:

$$P(F_{SM}) = \frac{1}{1 + e^{-(27.1908 - 1.0608m)}} \tag{6.6}$$

Solving equations (6.5) and (6.6) for m when the probabilities are 0.5, as described previously, determined that the boundary between fire spread being a failure or marginal was when the elevated fuel moisture content was 26%. The boundary between marginal and successful fire spread was when the elevated fuel moisture content was 19%. The plot of the observations from the fire spread experiments, probability curves and boundaries for success/marginal and marginal/failure is displayed in Figure 6.4. As with the ignition data, most of the observations were classified correctly (89%).

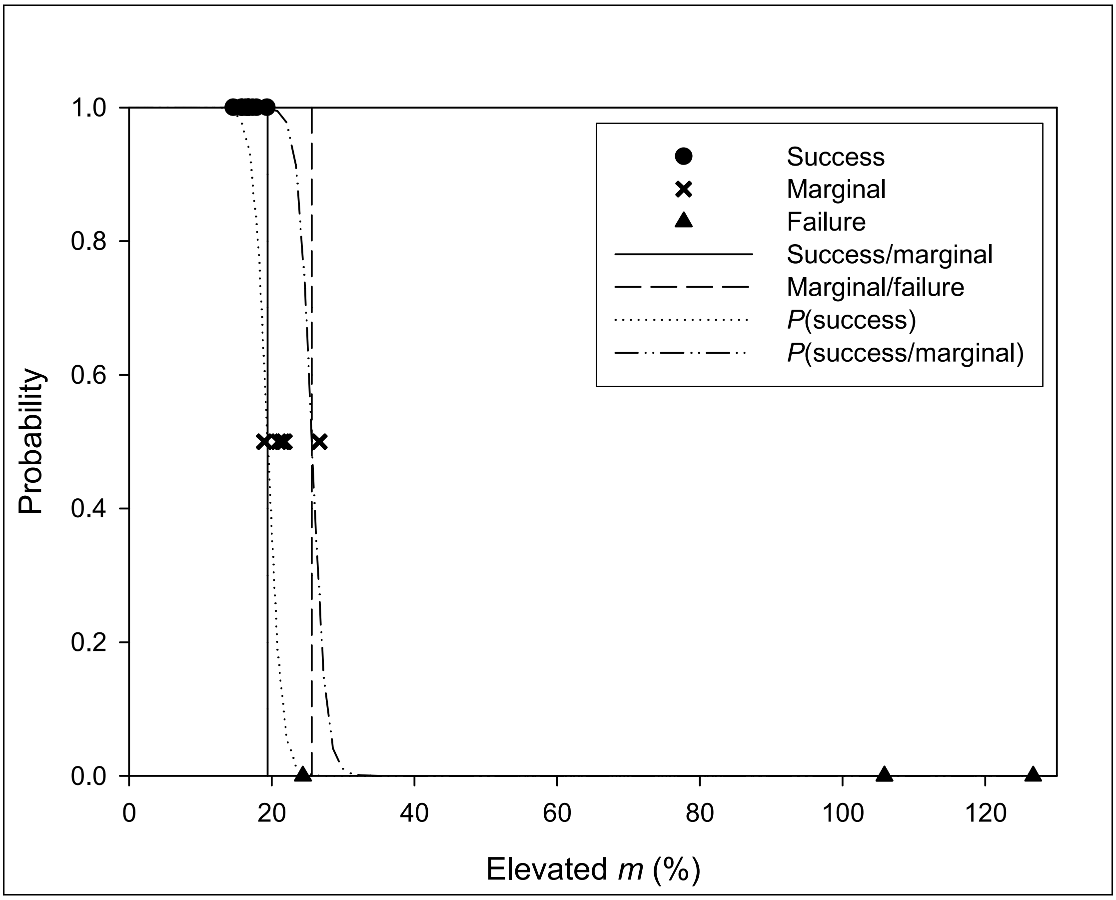


Figure 6.4. Plot of fire spread data (categorised into success, marginal or failure), with the probability plots from Equations (6.5) and (6.6), and the lines demarcating the success/marginal and marginal/failure boundaries.

Table 6.6. Model statistics for the analysis of the fire spread data, indicating suitability of models based on elevated m, near-surface m and FFMC. *P*-values are given in parentheses, where relevant (in all cases $n = 19$, except for 2 m wind where $n = 12$).

Non-significance for the deviance goodness-of-fit test indicates a good fit for the model, whilst significance for the likelihood ratio χ^2 test indicates good explanatory power in the model.

	Elevated *m* (%)	**Near-surface *m* (%)**	**Fuel height (m)**	**FFMC**	**ISI**	**10 m wind (km h^{-1})**	**2 m wind (km h^{-1})**	**1.5 m wind (km h^{-1})**
Likelihood ratio χ^2	27.65 (<0.0001)	13.24 (0.0003)	4.65 (0.0311)	26.45 (<0.0001)	27.24 (<0.0001)	3.20 (0.0736)	2.64 (0.1039)	5.02 (0.0251)
Akaike Information Criterion (AIC)	17.00	31.15	40.01	18.20	17.41	41.45	29.72	39.64
Schwarz Criterion (SC)	19.84	34.25	42.84	21.04	20.25	44.29	31.18	42.47
Deviance goodness-of-fit	11.00 (0.9999)	25.42 (0.8245)	20.14 (0.1665)	12.20 (0.9996)	11.41 (0.9998)	35.45 (0.3533)	23.72 (0.2070)	30.86 (0.1936)
c statistic	0.982	0.882	0.750	0.973	0.973	0.682	0.708	0.695

6.4. *Discussion*

The results from this study support field observations from the ignition and fire spread experiments, and the experience of fire managers, that thresholds in gorse fuels for ignition and those for fire spread differ. The results also indicate that the moisture content of the elevated dead fine fuels is the best predictor of both ignition and fire spread. This again correlates well with field observations, where fire behaviour experiments carried out in gorse fuels in New Zealand have shown some fires to develop and spread in the elevated dead fuel layer, independently of the surface litter layer (Scion, unpubl. data). Observations and anecdotal evidence from prescribed burning operations and wildfires also corroborate this finding (pers. obs.). This is explained by the large amounts of elevated dead fine fuel suspended in the canopy layer in gorse vegetation. Experimental fires were observed to spread successfully under conditions where the surface fuels hardly burned at all and definitely did not contribute to fire spread (a surface moisture content of 177% was recorded during an experiment where the fire spread successfully through the plot). Successful fire spread was also recorded during an experiment when the near-surface dead fuel layer had a sampled moisture content of 115%. Wind speed was not found to be a significant variable. These results are consistent with other studies which have found fuel moisture content to be the most important variable determining fire initiation and spread (e.g., McCaw, 1995; Plucinski & Anderson, 2008).

A summary of the threshold values governing ignition and fire spread is contained in Table 6.7. The threshold value of 36% for m, above which ignitions are predicted to be unsuccessful, seems reasonable, given that the fibre saturation level for fuels is generally around 35% moisture content (Cheney, 1981). The moisture content values have also been converted to the corresponding Fine Fuel Moisture Code (FFMC) value of the FWI System using equation (5.4). The FFMC value of 69.5 (based on 36% fuel moisture content) for ignition failure also compares favourably with Canadian guidelines which indicate that fires will begin to ignite at FFMC values of 70 and above (Alexander, 1991; de Groot, 1987).

Table 6.7. Fire management guidelines for ignition and fire spread success in gorse.

Elevated *m* (%)	FFMC	Ignition	Fire Spread
> 36%	< 69.5	NO	NO
30 – 36%	69.5 – 73.9	MARGINAL	NO
26 – 30%	74.0 – 77.0	YES	NO
19 – 26%	77.0 – 82.7	YES	MARGINAL
< 19%	> 82.7	YES	YES

Further investigation of the effect of wind speed and additional data collection from a greater range of wind and fuel moisture conditions is necessary. It was very difficult to obtain conditions of simultaneously high fuel moisture and high wind speed, since higher wind speeds during the study periods were generally associated with drying of fuels. In addition, this study did not consider other factors that may influence fire development in gorse fuels, such as slope and fuel characteristics (density, proportion of dead fuel, fuel age, etc.). Slope was specifically excluded from the experiments to avoid introducing further variability to the data. In New Zealand, gorse is often found in large, even-aged stands with little variation in height and fuel structure and this was reflected at the study sites. However, further exploration of these other factors on fire development is recommended.

The results also indicate that gorse fuels will support ignition and sustain fire spread under slightly higher levels of fuel moisture than those for other fuel types. Woodman and Rawson (1982) found that dead needles in the surface layer in *P.radiata* stands will just ignite and only carry fire under the influence of wind at a moisture content of 20-25%, and that surface needles will not ignite and elevated dead needles only just ignite and carry fire under the influence of wind at a moisture content of 25-30%. Luke and McArthur (1978) stated that fires would continue to burn in conifer plantations at fuel moisture contents of 25-30%. Plucinski and Anderson (2008) determined the threshold moisture content for successful ignition in *P.radiata* litter beds to be around 30%. Fernandes *et al.* (2008) found a fine dead surface fuel moisture content of around 35% to be the threshold for self-sustaining fires in *P.pinaster* with a *U.minor* understory in northern Portugal. Ignition is considered difficult and fire spread difficult to sustain in the range of 16-20% surface moisture content in Eucalypt forest litter in Australia (Luke & McArthur, 1978; Tolhurst & Cheney, 1999). McCaw (1995) found that the litter layer of *Eucalyptus tetragona* mallee-heath in Western Australia would only sustain ignition and fire spread at moisture contents below 8%. Marsden-Smedley *et al.* (2001) established dead fuel moisture content thresholds of 17% and 60% to delineate sustaining and marginal fires and marginal and non-sustaining fires respectively in Tasmanian buttongrass moorlands. However, wind speed and site quality were also important. de Groot *et al.* (2005) determined an ignition threshold of 35% dead fuel moisture content for tropical grassland fuels.

The effectiveness of operational implementation of these results will depend on the ability to accurately determine fuel moisture content of the elevated dead fuel layer in gorse fuels. This is difficult to measure directly at landscape scale, so reliable models of moisture prediction are essential to provide this information for fire managers. Current work on modelling moisture in these fuels will assist with providing reliable estimates of elevated dead fuel moisture (Anderson & Anderson, in press).

The results from this study provide useful guidelines for fire management decision-making in relation to gorse fuels in New Zealand. This study indicated that there were definite and separate thresholds for ignition and fire spread. From a fire management perspective, it is the conditions under which fires will develop and spread that are usually of most importance for determining levels of preparedness and response. It may be that lower levels of preparedness and response are required under conditions when fires will ignite but not spread, since the risk of spreading fires that require suppression effort and may pose a threat to life and property is reduced. The thresholds produced from this study will also be useful for setting prescriptions for safe prescribed burning operations and issue of permits.

Further data would be useful to validate and improve these models, in particular under conditions of high wind speed and high fuel moisture, to clarify the effect of wind speed on ignition and fire spread success. It would also be helpful to validate and extend the models to gorse communities in other parts of the world (such as Europe) that have a greater variety in fuel structure. Extending this modelling approach to other shrub fuels would provide fire management agencies with accurate information for a range of shrub fuel types. Notwithstanding these limitations, the results presented in this paper provide fire managers with guidelines that are based on sound scientific data collected in the field, and do appear to correlate well with field observations and the practical knowledge of fire development in these fuel types.

Chapter 7:
Shrub fire danger rating

7.1. Introduction

The objective of this chapter is to explore options to improve the system for rating fire danger in New Zealand shrub fuels that incorporate the results from previous chapters. Whilst the focus of this thesis has been on gorse fuels, the New Zealand Fire Danger Rating System (NZFDRS) classes all shrub fuels together as 'scrubland' (refer Chapter 2). The NZFDRS determines fire danger conditions on a daily basis across the country for forest, grassland and shrubland fuels. The fire danger classes of 'Low', 'Moderate', 'High', 'Very High' and 'Extreme' are based on head fire intensity that is linked to fire suppression requirements (Table 2.1). The New Zealand Scrubland Fire Danger Rating model was developed and released for operational use in 2000 (Anderson, 2009; Pearce, 2000a). This model follows a similar approach to that used for fire danger rating in forest and grassland fuels, with fire danger classes based on head fire intensity. The boundaries that define these fire danger classes are based on a standardised fuel load, wind speed and the Fine Fuel Moisture Code (FFMC) from the Fire Weather Index (FWI) System. The current model to predict rate of fire spread in shrub fuels in New Zealand is a critical component to determine the fire danger classes, and this model is described prior to an overview of the current fire danger rating model.

Shrub rate of fire spread model

The model to predict rate of fire spread in New Zealand shrub fuels was developed following the Canadian approach and is based on an S-shaped asymptotic curve to model rate of spread (*r*) in m h^{-1}:

$$r = a * \left[1 - e^{(-b*ISI)}\right]^{c} \quad , \qquad (7.1)$$

where ISI is the Initial Spread Index from the FWI System, and *a*, *b* and *c* are parameters specific to a fuel type. This general equation was fitted to New Zealand data from 29 experimental burns and 3 wildfires to give the following model:

$$r = 4920 * \left[1 - e^{(-0.1 * ISI)}\right]^{1.5} \quad , \tag{7.2}$$

Data used to fit the model comprised observations from a range of shrub fuel types, including gorse, manuka/kanuka and wetland fuels with a mix of shrub fuels (pakihi, manuka/kanuka, other native hardwoods). The model fitted the data rather poorly (Figure 7.1), with R^2 = 0.45, ME = -142.63, RMSE = 666.65. In fact, a basic linear model described the relationship between ISI and rate of spread more satisfactorily (R^2 = 0.51, ME = 96.93, RMSE = 540.69). The sigmoidal shape for the current model was selected to represent the rapid initial increase in rate of spread and subsequent levelling-off at very high values of ISI (Forestry Canada Fire Danger Group, 1992). Data in the ISI range of 10-20 are scarce, with only two data points having values of greater than 8. These two points have very high leverage, and more data with high values of ISI are required (Anderson, 2009).

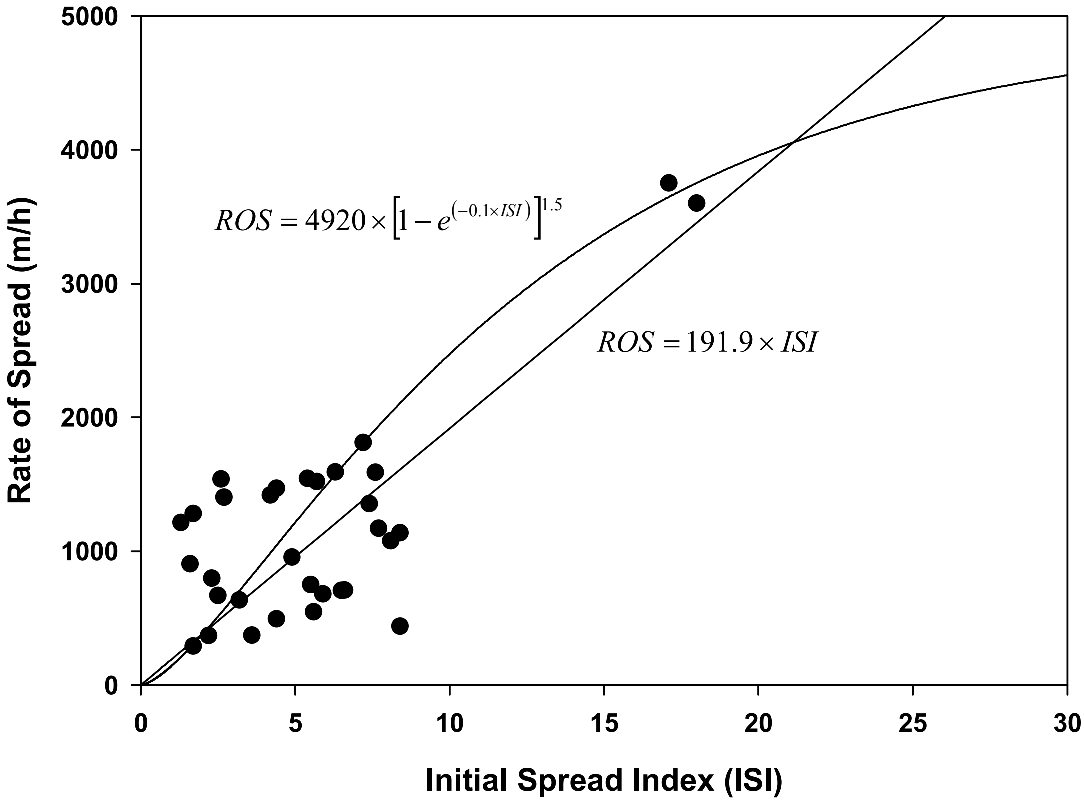


Figure 7.1. The current rate of spread model for New Zealand shrub fuels. A simple linear relationship is also overlaid on the fire data.

Scrubland Fire Danger Rating model

The first version of the NZ Scrubland Fire Danger Rating Model was released in 2000 (NZ Fire Research, 2000). It used the ISI to represent rate of fire spread and shrub height as a surrogate for fuel load. This model was problematic in that fire danger classes were narrowly defined, with the 'Low' fire danger class almost non-existent (Figure 7.2). Fire managers provided feedback that the model almost always predicted 'Extreme' fire danger and was therefore of limited practical use. The model's lack of response to moist/damp conditions prompted a review, and it was then revised to its current format (Anderson, 2009; Pearce, 2000a, 2000b).

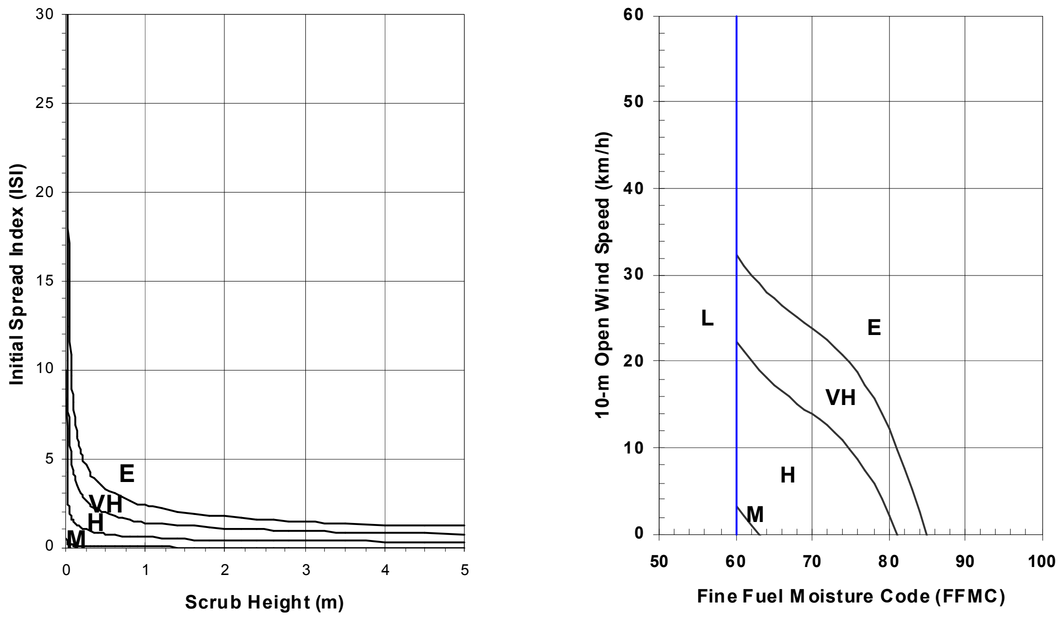


Figure 7.2. The first model for shrub fire danger rating (left) in New Zealand and the revised version currently in use (right).

The current model uses the Fine Fuel Moisture Code (FFMC) of the FWI System and the 10 m wind speed to determine fire danger classes (Figure 7.2). The FFMC combined with wind speed is effectively the Initial Spread Index. The system also assumes a standard shrub fuel load of 20 t ha^{-1} across the country and includes an FFMC threshold value of 60, below which the fire danger class is always 'Low'. This threshold value was based on limited observations of ignition and fire spread success during fire experiments (Pearce, 2000a). The standard fuel load of 20 t ha^{-1} was based on the fuel models developed for NZ shrub fuels (Fogarty & Pearce, 2000). This removed the need for fire managers to assess fuel loads across the country for different areas of shrub fuels. The threshold FFMC value of 60 provided an improved response to moist conditions over the previous version, where ‘Very High’ or ‘Extreme’ fire danger was possible at high fuel moisture levels. The corresponding values of wind speed and FFMC that define the fire danger class boundaries were calculated to facilitate plotting of these classes on the graph (Figure 7.2). The method used to calculate these values is described in Section 7.2. However, this revised model still predicts ‘Extreme’ fire danger too frequently. A recent study found that the average annual number of days of ‘Very High’ and ‘Extreme’ fire danger in shrub fuels across the country ranged from 104-294 days, or 28-81% of the total days of the year (Pearce *et al.*, 2003). The assumed standard fuel load of 20 t ha^{-1} requires validation, as does the FFMC threshold value of 60 (Anderson, 2009).

7.2. Methods

A series of experimental burns have been carried out in shrub fuels in New Zealand since 1992 by Scion’s Rural Fire Research Group (Pearce & Doherty, 2008). Data from these experiments were used to explore methods for rating fire danger in New Zealand shrub fuels. The original database used to develop the rate of spread model (Section 7.1) contained 35 fire observations, including three wildfires. Wildfire observations and observations of fires on slopes and in wetlands were removed for this study. This provided a dataset of 25 observations, comprising 10 fire experiments in gorse fuels and the remaining 15 in native shrub fuels, manuka and kanuka. Given the relatively low number of fire experiments in gorse, data from the gorse and manuka/kanuka fire experiments were combined. Observations from fire experiments on slopes were omitted, since slope has a significant effect on rate of spread and fire intensity and correcting observations for slope is currently limited to relationships for forest fuel types (Cheney, 1981; Forestry Canada Fire Danger Group, 1992; Van Wagner, 1977). Corrections developed for other fuel types are not necessarily valid for fires in shrub fuels on slopes. Wildfire observations lacked data on fuel moisture content and fuel consumption. Wetland fire observations contained uncertain mixes of shrub and other fuels, such as sedges, rushes and grasses that were considered unrepresentative of pure shrubland fuels.

The database contained a range of variables for each fire experiment, including: rate of spread (m h^{-1}), head fire intensity (kW m^{-1}), wind speed (measured at 10 m above ground in km h^{-1} or converted to 10 m-equivalent), moisture content and fuel consumption (t ha^{-1}) from post-fire sampling. Hourly values of the FFMC and ISI components of the FWI System were calculated for each fire experiment using the sampled dead fine fuel moisture content of the elevated fuel and wind speed at the time of the fire experiments, as per Alexander *et al.* (1984). Values of head fire intensity (*I*) were calculated based on Byram's equation (Brown & Davis, 1973) converted to metric form (Alexander, 1982):

$$I = Hwr\,, \qquad (7.3)$$

where *I* is fire intensity (kW m^{-1}), *H* is the net low heat of combustion (kJ kg^{-1}), *w* is the weight of fuel consumed per unit area (kg m^{-2}) and *r* is the rate of fire spread (m s^{-1}). *H* is generally assumed to be constant at approximately 18000 kJ kg^{-1} (Beck *et al.*, 2002), and a simplified formula for calculation of *I* is:

$$I = \left(\frac{w * r}{2}\right), \qquad (7.4)$$

with *w* the fuel load or fuel consumed (t ha^{-1}) and *r* the rate of fire spread (m h^{-1}).

Wind speed and FFMC values that define the fire danger classes were calculated for the current Scrubland Fire Danger Rating model by solving equation (7.4) for *r*, using the standard fuel load (20 t ha^{-1}) and known *I* (boundary values of the fire danger classes). The corresponding value of ISI for each fire danger class was then calculated using equation (7.2), the current model to predict rate of spread in New Zealand shrub fuels. The wind speed corresponding to values of FFMC was then calculated from the standard FWI System equations for the ISI, as described by Van Wagner (1987).

The current Scrubland Fire Danger Rating Model assumes a standard shrub fuel load across the country of 20 t ha^{-1}. However, observations in the database of fire experiments provided values of head fire intensity based on fuel consumption and rate of spread (equation 7.4), and therefore did not incorporate the standard fuel load of 20 t ha^{-1}. It was therefore necessary to convert the observed rate of spread and intensity values to those based on the standard fuel load of 20 t ha^{-1} to allow comparison against the current Scrubland Fire Danger Rating model. In addition, the standard fuel load value was varied to determine whether a standard fuel load other than 20 t ha^{-1} provided a better fit to the data. Alternative fuel load values tried were 15, 25, 30 and 35 t ha^{-1}. Corresponding fuel heights for these standard fuel load values are shown in Table 7.1. Firstly, a basic model was developed using linear regression to predict rate of spread (r) from fuel consumption (w) and wind speed (u). The data were transformed to reduce variability using the natural logarithms of r, w and u. This yielded the following model:

$$\ln(r) = 3.872 + 0.561 * \ln(u) + 0.428 * \ln(w), \qquad (7.5)$$

which provided a reasonable fit to the data with $R^2 = 0.52$, F-value = 13.90, p = 0.0001 (Figure 7.3). One observation with a very high rate of spread (3600 m h^{-1}) is prominent in Figure 7.3. This was from a fire experiment with a considerably shorter fire run of 40 m (as opposed to the standard of 100 m) and was carried out under the highest wind speed (36.7 km h^{-1}) of all of the fire experiments. The wind speed closest to this observation was 26 km h^{-1}.

(a) (b)

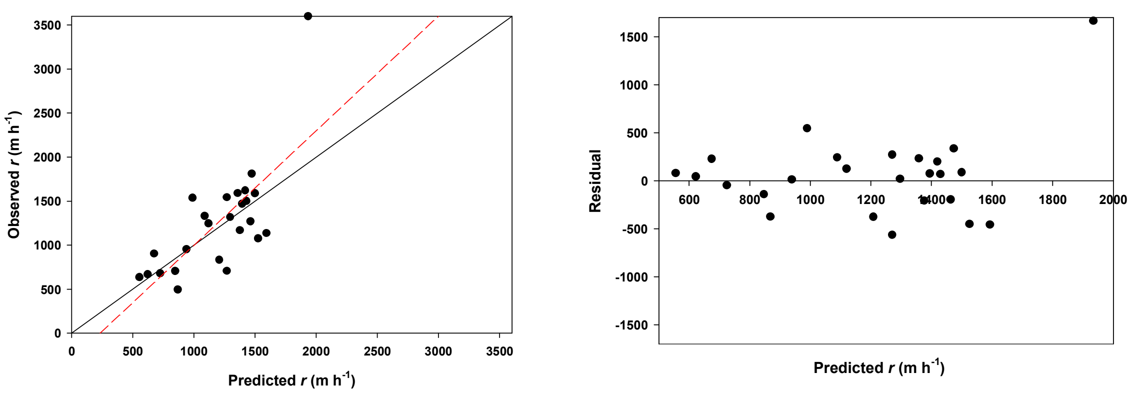


Figure 7.3. Plot of the observed against predicted rate of spread (r) values (a) and residuals (b) using equation (7.5).

Equation (7.5) was then used to predict rate of spread for a standard fuel load:

$$r_x = \left(\frac{x}{w}\right)^{0.428} * r \, , \qquad (7.6)$$

where r_x is the rate of fire spread (m h^{-1}) based on the standard fuel load x (t ha^{-1}), and w is the fuel load that corresponds to the fire observation.

The equation to calculate fire intensity based on a standard fuel load and following the form of equation (7.4) was:

$$I_x = \frac{x * r_x}{2} \, , \qquad (7.7)$$

where I_x is the head fire intensity (kW m^{-1}) at the standard fuel load x (t ha^{-1}).

Attempts were made to improve the relationship between rate of spread (r) and ISI using the rate of spread corrected for the various standard fuel loads by equation (7.6). However, these relationships were generally poorer than the existing relationship in equation (7.2).

Table 7.1. Equivalent fuel height for different standard fuel load values, based on fuel load and fuel height relationships reported by Fogarty and Pearce (2000).

Standard fuel load (t ha^{-1})	**Gorse (m)**	**Manuka/kanuka (m)**
15	0.5	0.6
20	0.75	1.25
25	1.1	2.3
30	1.5	3.7
35	2.0	5.7

Estimates of fire intensity using the observations from the fire behaviour database as inputs to equation (7.7) indicated that nearly all of the intensity values were greater than 4000 kW m^{-1}. The few values that were below 4000 kW m^{-1} were greater than 3000 kW m^{-1}. As the majority of the observations fell into the 'Extreme' fire danger class (4000+ kW m^{-1}), this class was broken down into three levels to provide better delineation of the data. These revised fire danger classes and corresponding fire intensity ranges are shown in Table 7.2.

Table 7.2. Revised fire danger classes for shrub fuels as determined by experimental fire data.

Fire Danger Class	Head fire intensity (kWm^{-1})
Low	0-10
Moderate	10-500
High	500-2000
Very High	2000-4000
Extreme 1	4000-8000
Extreme 2	8000-12000
Extreme 3	12000+

Observations from the fire behaviour database, with head fire intensity recalculated for the relevant standard fuel load using equation (7.7), were then plotted using the procedure employed by the current Scrubland Fire Danger Rating model with the three levels of Extreme fire danger. Observations were allocated to fire danger classes based on their head fire intensity values (Table 7.2) and marked to differentiate between them.

An alternative approach to defining the fire danger classes was also tried. A single value of wind speed was used to define the boundaries of each fire danger class. Firstly the rate of spread corresponding to the lower boundary of the relevant fire danger class was calculated from equation (7.4), as employed by the current system. The wind speed defining the fire danger class boundary was calculated by then solving equation (7.5) for wind speed, using the rate of spread from equation (7.4) and the standard fuel load. These wind speed values defined the boundaries of the fire danger classes.

These different fire danger rating models were compared against each other by the percentage of the total number of observations (25) allocated to the correct fire danger classes.

7.3. Results

Plots of the two approaches used to define the fire danger classes, with observations from the fire behaviour database for the different standard fuel loads, are shown in Figures 7.4 to 7.8. Additional lines were inserted onto these graphs, representing the ignition and fire spread thresholds from Chapter 6 (see Table 6.7).

There were only a very small number of observations with head fire intensities less than 4000 kW m^{-1}: three at fuel load 15 t ha^{-1} and one at fuel load 20 t ha^{-1}. These observations were also all greater than 3000 kW m^{-1}. Of the 25 observations, 18 (72%) were above the FFMC threshold value of 82.7 indicating fire spread success (Table 6.7). A further four observations were reasonably close to this threshold value. In addition, all of the observations except one were higher than the FFMC threshold value of 69.5, below which ignition is expected to fail. The observation that was plotted close to the threshold line of FFMC 69.5 (FFMC 69.4, wind speed 28.3 km h^{-1}) was unusual. Notes from this fire experiment indicated that the sampled elevated dead fuel moisture content was possibly unreliable, presumably due to issues with sample collection. However, no further field notes were available to provide more clarity.

When using the first approach to define the fire danger classes for shrub fuels, the fire danger rating models based on standard fuel loads of 30 and 35 t ha^{-1} provided the best fit, with 80% of the 25 fire observations classified into the correct fire danger classes for both models (Table 7.3). The poorest fit was provided by the model based on a standard fuel load of 20 t ha^{-1} (24% correct). This is the fuel load used in the current national model for rating fire danger in shrub fuels. The 'Moderate' fire danger class disappeared from the models for standard fuel loads above 20 t ha^{-1}

(corresponding wind speed values were zero or negative when calculated from the ISI equation).

Using the second approach to define the fire danger classes with a constant wind speed for the boundary of each class, the most appropriate models were again those assuming fuel loads of 30 and 35 t ha^{-1}, with 84% of observations correctly classified for both. The current model based on a standard fuel load of 20 t ha^{-1} only classified 68% of the observations correctly. The model based on 25 t ha^{-1} provided the poorest fit, with only 56% of observations classified correctly. This approach resulted in the loss of both the 'Low' and 'Moderate' fire danger classes, with their boundaries calculated to be at wind speeds of 0 km h^{-1}. In addition, for all of the models the 'High' and 'Very High' fire danger classes were defined by very narrow ranges of wind speed. These models indicated that under conditions of even low wind speed, fire danger would often fall into the 'Extreme 1' fire danger class (e.g., 4.4 km h^{-1} for standard fuel load 20 t ha^{-1}, 1.6 km h^{-1} for 30 t ha^{-1}).

Table 7.3. Percentage of the total number of fire observations (n = 25) from the fire database allocated to the correct fire danger classes, based on head fire intensity (Table 7.2). 'Standard' refers to the current method of shrub fire danger rating and 'Alternative' to the approach that used a single wind speed value to define the fire danger class boundaries.

Fuel load	Standard model	Alternative model
15	32%	68%
20	24%	68%
25	56%	56%
30	80%	84%
35	80%	84%

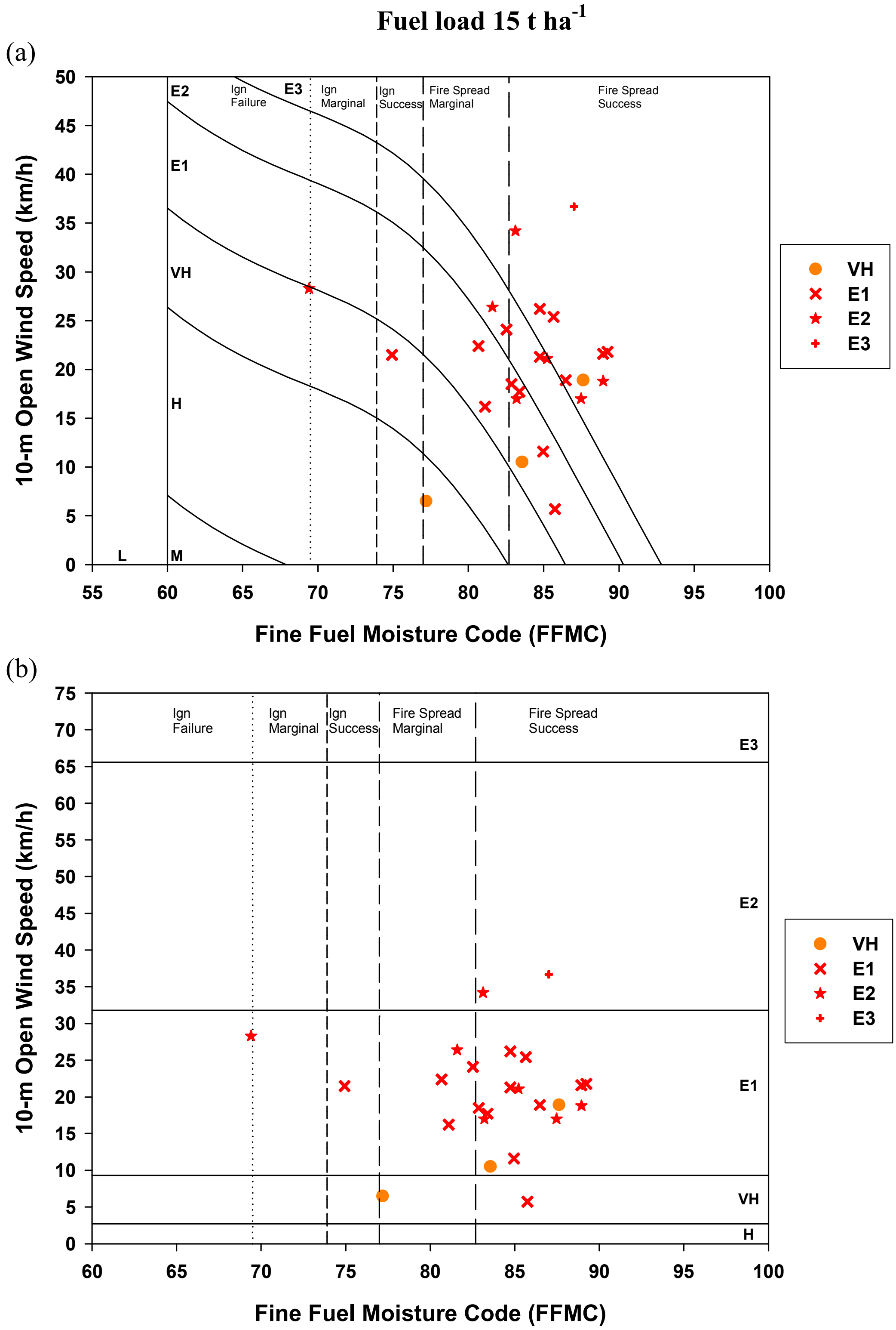


Figure 7.4. Plot of experimental fire observations (gorse and manuka/kanuka shrub) by fire danger class, assuming a standard fuel load of 15 t ha^{-1}. Plot (a) represents the current approach to define the fire danger class boundaries, and plot (b) uses a single wind speed value to define the boundaries. Additional vertical (dashed and dotted) lines represent the ignition and fire spread boundaries as described in Chapter 6 (Table 6.7).

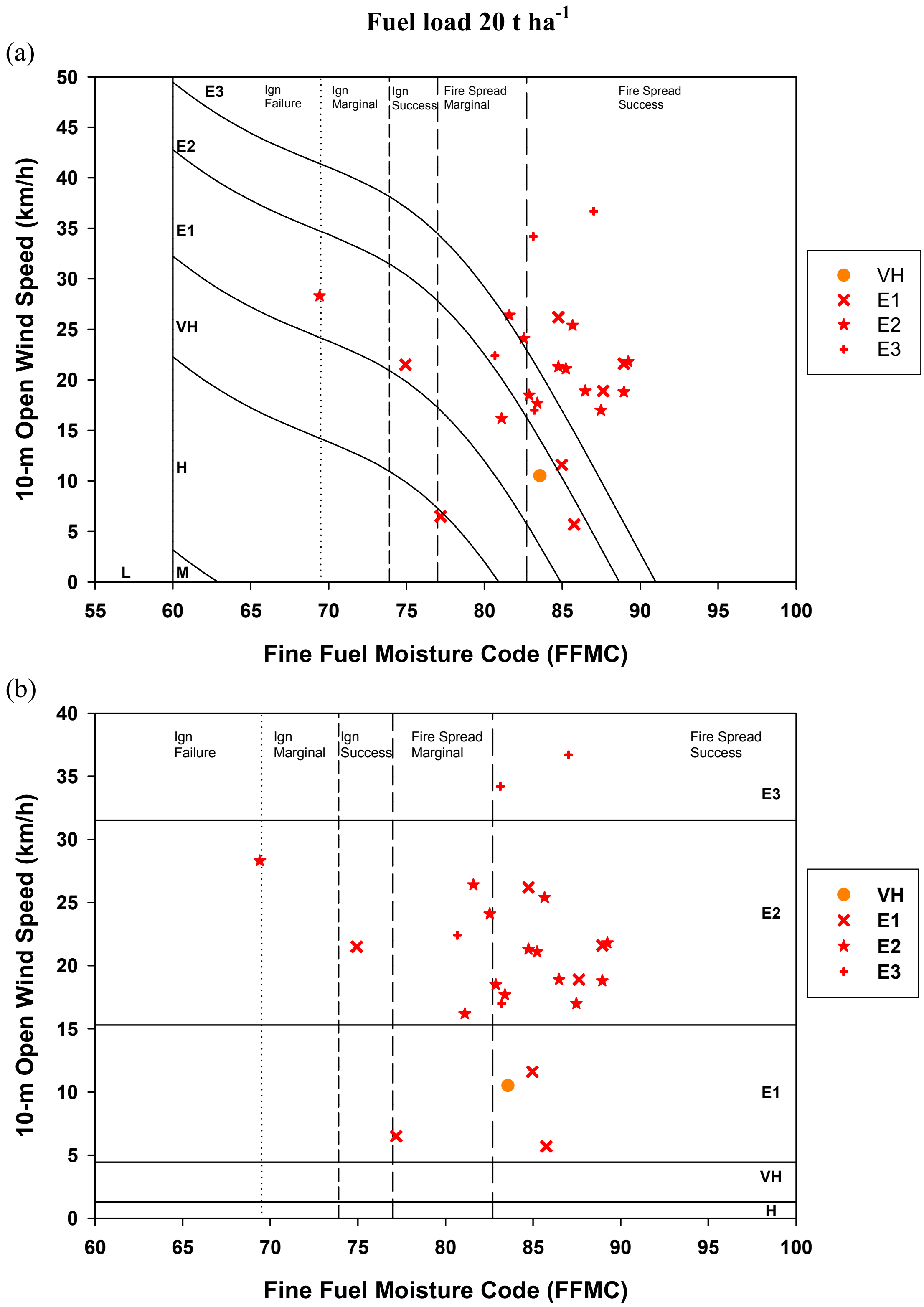


Figure 7.5. Plot of experimental fire observations (gorse and manuka/kanuka shrub) by fire danger class, assuming a standard fuel load of 20 t ha^{-1}. Plot (a) represents the current approach to define the fire danger class boundaries, and plot (b) uses a single wind speed value to define the boundaries. Additional vertical (dashed and dotted) lines represent the ignition and fire spread boundaries as described in Chapter 6 (Table 6.7).

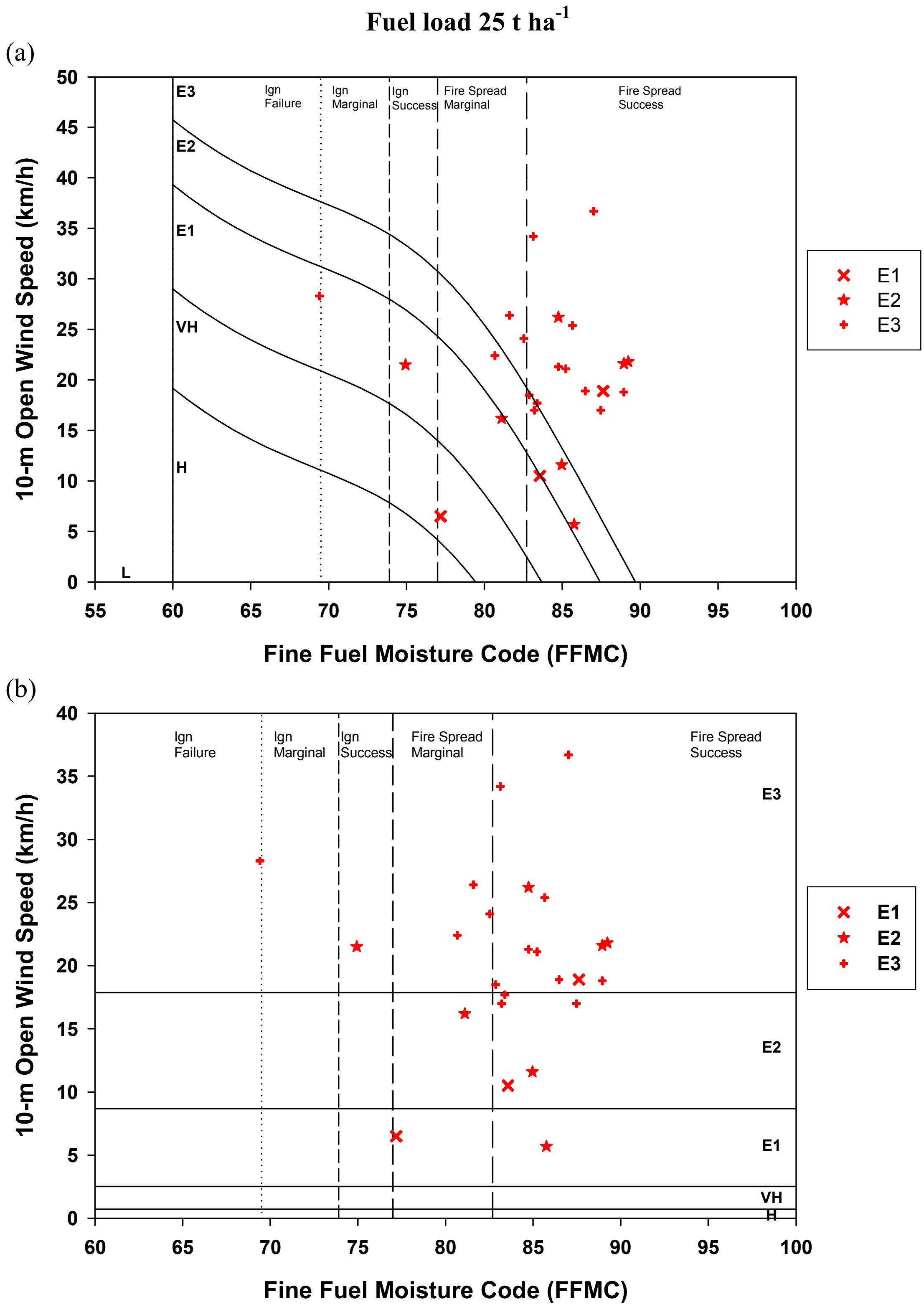
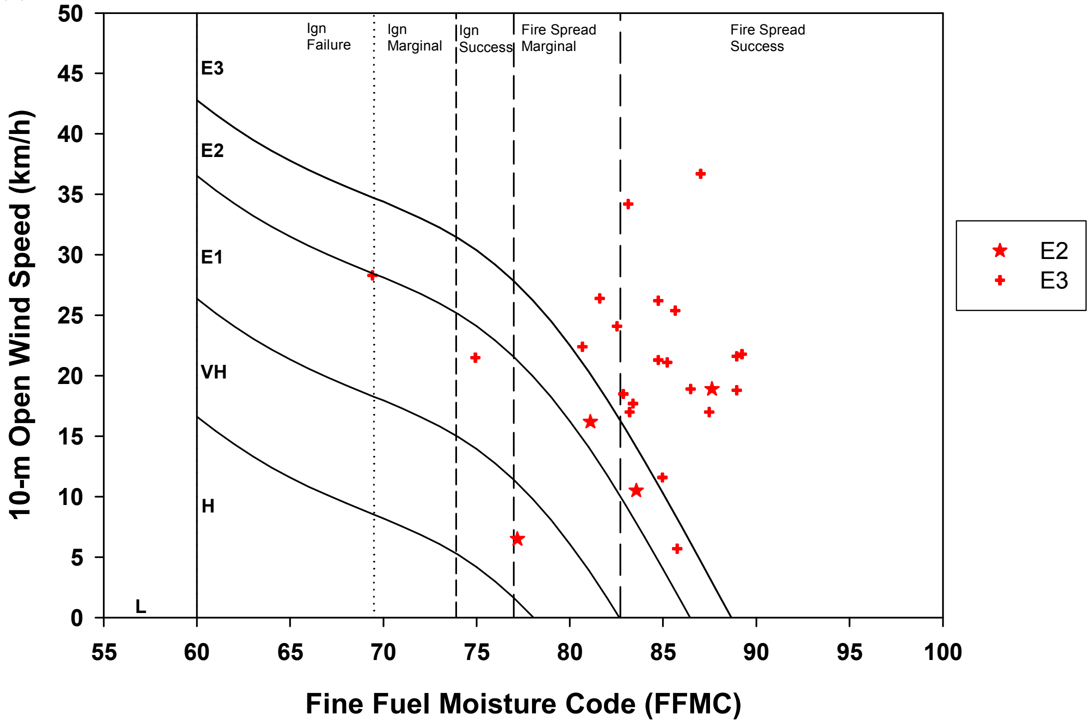


Figure 7.6. Plot of experimental fire observations (gorse and manuka/kanuka shrub) by fire danger class, assuming a standard fuel load of 25 t ha^{-1}. Plot (a) represents the current approach to define the fire danger class boundaries, and plot (b) uses a single wind speed value to define the boundaries. Additional vertical (dashed and dotted) lines represent the ignition and fire spread boundaries as described in Chapter 6 (Table 6.7).

Fuel load 30 t ha^{-1}

(a)



(b)

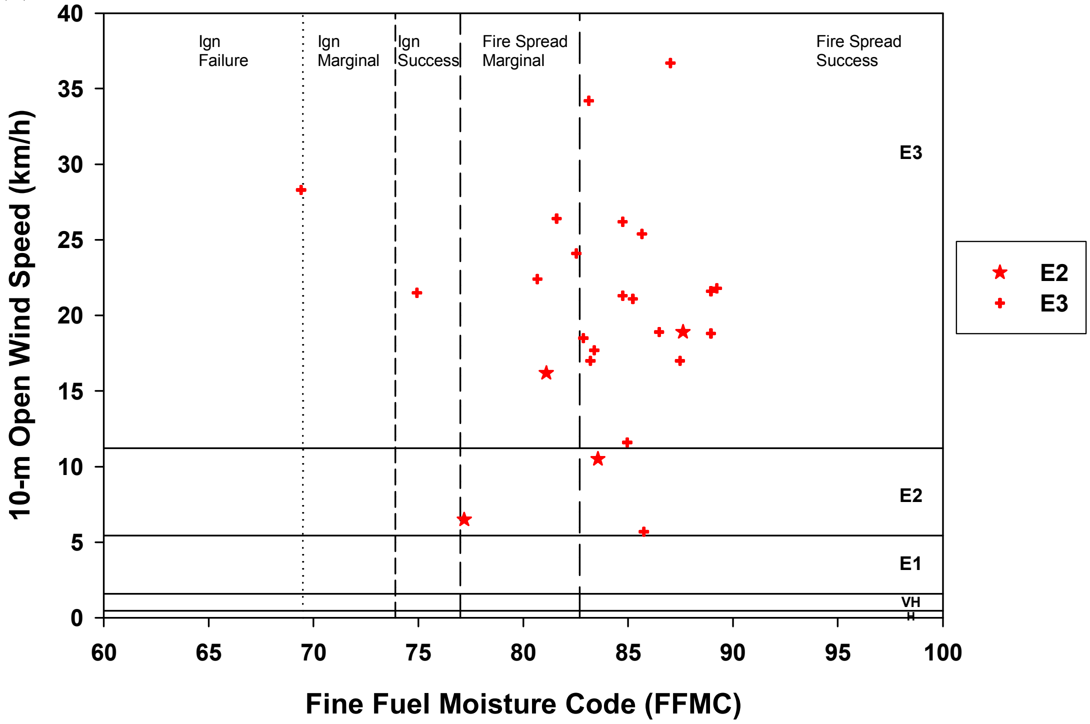


Figure 7.7. Plot of experimental fire observations (gorse and manuka/kanuka shrub) by fire danger class, assuming a standard fuel load of 30 t ha^{-1}. Plot (a) represents the current approach to define the fire danger class boundaries, and plot (b) uses a single wind speed value to define the boundaries. Additional vertical (dashed and dotted) lines represent the ignition and fire spread boundaries as described in Chapter 6 (Table 6.7).

Fuel load 35 t ha^{-1}

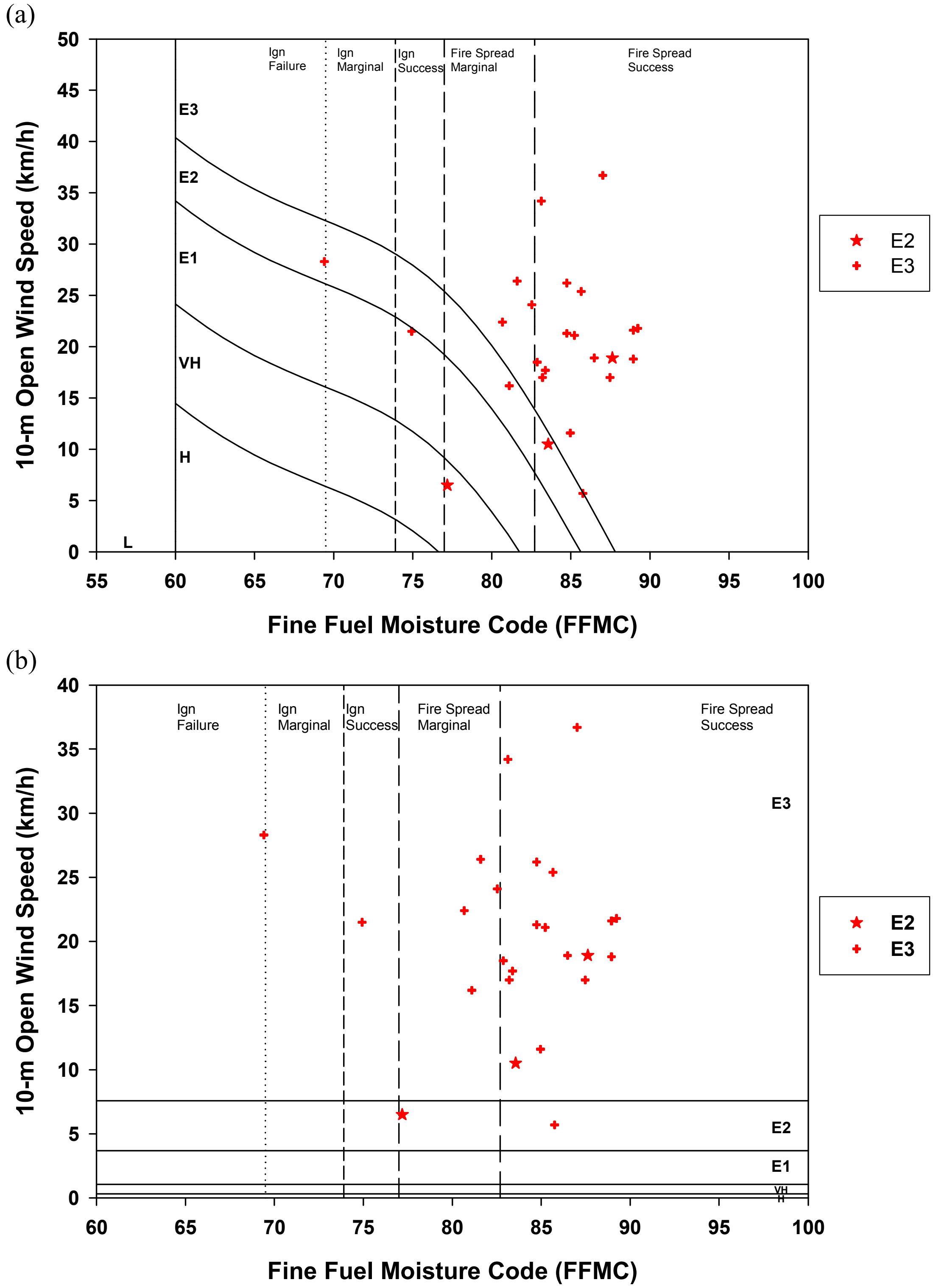


Figure 7.8. Plot of experimental fire observations (gorse and manuka/kanuka shrub) by fire danger class, assuming a standard fuel load of 35 t ha^{-1}. Plot (a) represents the current approach to define the fire danger class boundaries, and plot (b) uses a single wind speed value to define the boundaries. Additional vertical (dashed and dotted) lines represent the ignition and fire spread boundaries as described in Chapter 6 (Table 6.7).

7.4. *Discussion*

Results indicated that the thresholds for ignition and fire spread derived for gorse (Chapter 6) may also be applicable to manuka/kanuka shrub fuel types, since the thresholds appear to be appropriate when tested against the 25 fire observations from a range of sites and shrub fuel complexes. All of the observations except one were higher than the FFMC threshold value of 69.5, below which ignition is expected to fail. The observation that was not above this threshold value was in fact very close to it, with an FFMC value of 69.4. As previously noted, this observation was unusual and the sampled elevated dead fuel moisture content was possibly unreliable. A large number of the observations (72%) were also higher than the FFMC threshold value of 82.7, indicating fire spread success.

The results from using the current approach for fire danger rating in shrub fuels indicated that the models based on either a standard fuel load of 30 or 35 t ha^{-1} were most suitable. Both of these models classified 80% of all the 25 fire observations into the correct fire danger classes. The model currently used nationally for fire danger rating, that uses a standard fuel load of 20 t ha^{-1}, classified only 24% of observations correctly. This was the lowest percentage of correct classifications for all of the models tested.

Increasing the standard fuel load reduced the values of FFMC and wind speed that defined the lower boundaries of the fire danger classes. Considering the fuel height that is represented by the standard fuel load (Table 7.1), a fuel load of 35 t ha^{-1} corresponds to gorse of 2.0 m and manuka/kanuka of 5.7 m. A standard fuel load of 30 t ha^{-1} corresponds to gorse of 1.5 m and manuka/kanuka of 3.7 m. The current model (standard fuel load 20 t ha^{-1}) represents gorse of 0.8 m and manuka/kanuka of 1.3 m. The average fuel load and fuel height for the 9 gorse observations contained in the fire behaviour database were 38.5 t ha^{-1} (±14.0) and 2.4 m (±1.1) respectively. For the 16 manuka/kanuka observations, average fuel load was 32.0 tha^{-1} (±12.4) and average fuel height was 2.3 m (±1.3). There was therefore significant variability in the fuel height between observations.

The model using a standard fuel load of 35 t ha^{-1} was probably unrepresentative in terms of fuel height, particularly in the case of manuka/kanuka (corresponds to a fuel height of 5.7 m). The model using a standard fuel load of 30 t ha^{-1} was therefore regarded as the most appropriate one, because it implies a gorse height of 1.5 m and a manuka/kanuka height of 3.7 m. Whilst the manuka/kanuka height of 3.7 m is taller than the average of the 16 field observations from the fire experiments (2.3 m), this taller height is not regarded as unusual when more recent work undertaken in these fuels in the high country areas of Canterbury is considered (Pearce & Gould, 2005). This is also well within the range of fuel height data collected for manuka/kanuka across the country to develop the current fuel load models (Fogarty & Pearce, 2000; Manning & Pearce, 2008). Furthermore, the 20 t ha^{-1} fuel load (and corresponding fuel heights) for the current fire danger rating model were recognised to be conservative estimates in the development of the model (Pearce, 2000a).

Selecting standard fuel loads higher than 20 t ha^{-1} resulted in the loss of the 'Moderate' fire danger class. However, the 'Low' fire danger class still existed for any value of FFMC less than 60 (representing the threshold for successful ignitions). Results from the ignition threshold modelling work in Chapter 6 (and Table 6.7) indicated that an FFMC value of 69.5 represented the ignition threshold for gorse fuels. Ignitions were failures below FFMC 69.5, marginal from 69.5 to 73.9 and successful at values higher than 73.9. The boundary for the 'Low' fire danger class was therefore changed to an FFMC value of 69.5. However, there was still a problem with the 'Moderate' fire danger class not being present, meaning that fire danger would move directly from 'Low' to 'High'. This defies the logic of a fire danger rating system, which is intended to represent the gradual increase in fire behaviour conditions through classes. The three levels of 'Extreme' fire danger could also have the potential to cause confusion amongst fire managers and the general public, since there is only one 'Extreme' class for forests and grasslands. Currently the fire danger rating system is colour-coded by green ('Low'), blue ('Moderate'), yellow ('High'), orange ('Very High') and red ('Extreme') (Alexander, 2008). An alternative approach was considered to change the nomenclature of the fire danger classes from the current form of 'Low' to 'Extreme' to numbered classes. A similar approach has been used in parts of Canada, where fire behaviour potential is described in ranks or classes (e.g., Alexander & Cole, 1995; BC Ministry of Forests, no date; Taylor *et al.*, 1997). These alternative classes and their corresponding levels of fire potential/intensity are shown in Table 7.4.

Table 7.4. Proposed alternative classification system for rating fire danger in shrub fuels.

Fire Danger Class	Range (FFMC & head fire intensity, kW m^{-1})	Description/ equivalence
1	FFMC <69.5	Low
2	FFMC ≥69.5 & <2000 kW m^{-1}	High
3	2000-4000	Very High
4	4000-8000	Extreme 1
5	8000-12000	Extreme 2
6	12000+	Extreme 3

The graph of fire danger classes using a standard fuel load of 30 t ha^{-1} is shown in Figure 7.9, with fire observations plotted onto the fire danger classes as defined in Table 7.4.

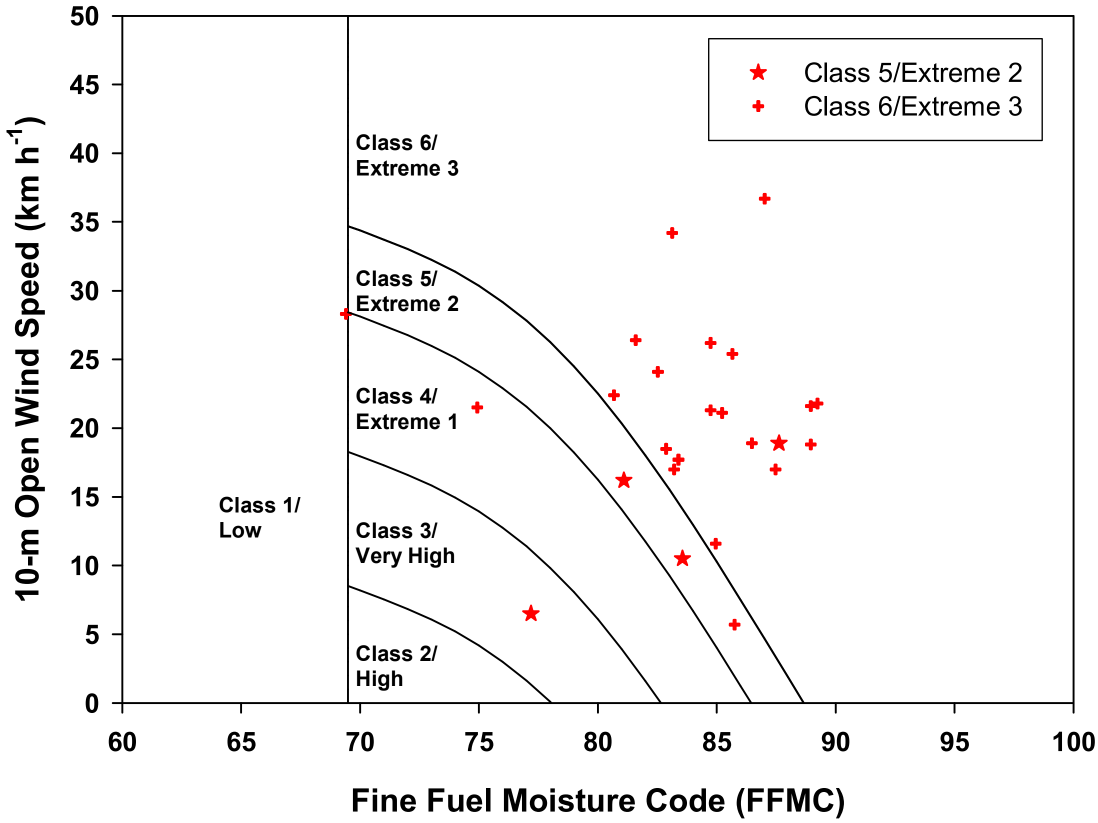


Figure 7.9. The current shrubland fire danger rating model, modified to represent a standard fuel load of 30 t ha^{-1} and with fire danger classes as defined in Table 7.4.

For the alternative approach using a constant wind speed to define each fire danger class, the models based on standard fuel loads of 30 and 35 t ha^{-1} were again the best, with 80% of the observations classified correctly in both cases. The model using a standard fuel load of 20 t ha^{-1} only classified 68% of the observations correctly. Based on the previous discussion of fuel heights corresponding to fuel loads, it is again more appropriate to select the model using a standard fuel load of 30 t ha^{-1} than that using 35 t ha^{-1}. This model is shown in Figure 7.10, with the same modifications as described for Figure 7.9. The range of wind speeds that defined the fire danger classes for this model was very narrow. The 'High' and 'Very High' fire danger classes were almost non-existent, with upper boundary values of 0.5 km h^{-1} and 1.6 km h^{-1} respectively. Therefore, with an FFMC value greater than 69.5 and wind speed over 2 km h^{-1}, this model predicts fire danger to be in 'Extreme 1/Class 4' with a head fire intensity greater than 4000 kW m^{-1}. Fire danger is in 'Extreme 3/Class 6' with a head fire intensity greater than 12000 kW m^{-1} when the wind speed exceeds 11.6 km h^{-1}.

'Extreme' fire danger represents fires of high intensity that are difficult, if not impossible, to control (Table 2.1). A model predicting extreme fire potential at wind speeds over 2 km h^{-1} would be of limited practical use to fire managers, since this would mean that the shrub fire danger would be in one of the 'Extreme' classes on most days of the year. However, this may be representative of the highly flammable nature of shrub fuels. Further data that covers the range of fire danger classes would allow more thorough evaluation of this alternative model. Currently all the observations fall into only two classes, 'Extreme 2/Class 5' and 'Extreme 3/Class 6'.

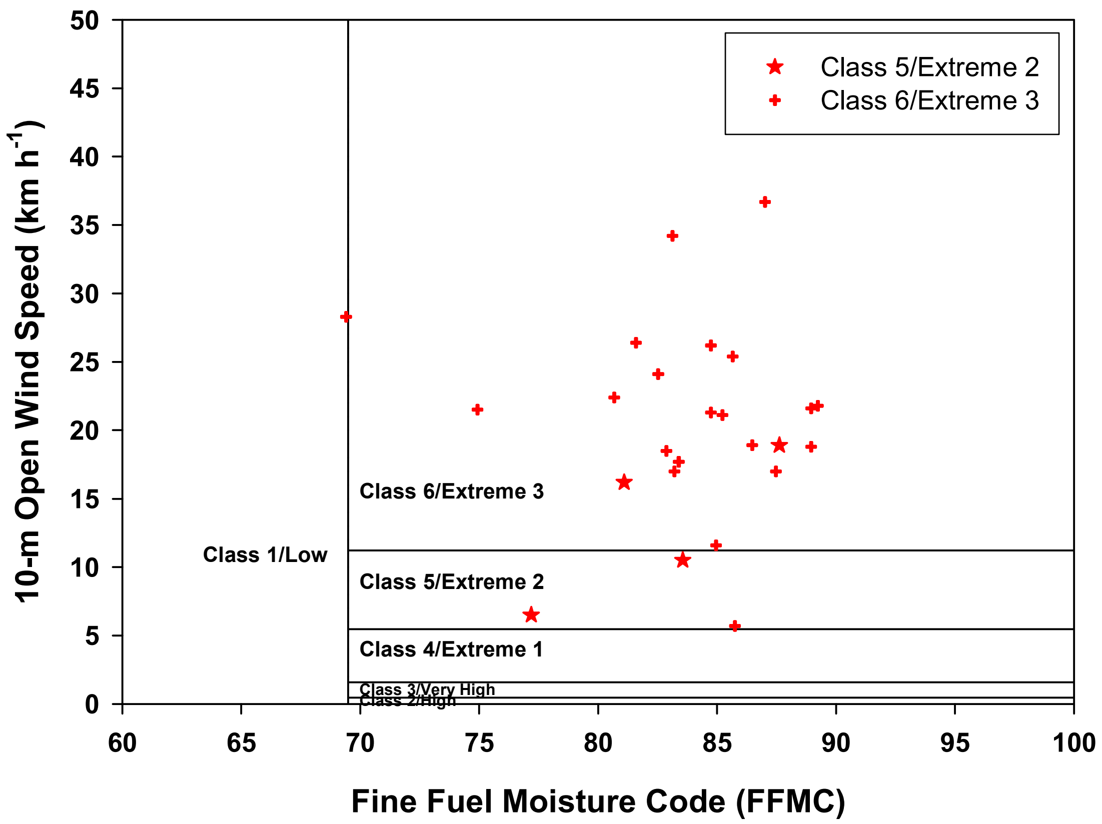


Figure 7.10. A shrubland fire danger rating model with fire danger classes defined by wind speed, based on a standard fuel load of 30 t ha^{-1}. Fire danger classes are defined as shown in Table 7.4.

Further data from experimental fires and wildfires are required to accurately define the fire danger classes and to provide a greater range of observations. There are currently no observations with fire intensities below 3000 kW m^{-1} for any of the standard fuel loads. However, it may be difficult to obtain such data, since fires in shrub fuels have been observed, both in this study and from the broader experimental fire data, to either struggle to ignite or to spread and burn with very high intensity. The ‘middle range’ of conditions, where fires burn at low or moderate intensity levels, appeared to be narrow or even absent in these fuels. Shrub fuels have been described as having an ‘on/off switch in terms of no ignition/no fire spread versus an extreme type rate of fire spread and intensity’ (Alexander, 2008). Wildfire data to validate the proposed models were also unsuitable. There were only four records from wildfires in New Zealand shrub fuels. Two were from fires on slopes and, as previously stated, the ability to correct fire spread observations for slope is currently limited. The other two records were from wetland areas not representative of pure gorse or manuka/kanuka shrub fuels, being a mix of shrub, grass and other wetland vegetation such as reeds and sedges.

The development of a robust shrub fire danger rating model also depends on a reliable model to predict the rate of fire spread in shrub fuels. Fire danger class boundaries were calculated differently for the two approaches presented. For the first approach, the boundaries of the fire danger classes were based on the wind-speed equivalent of the Initial Spread Index (ISI). This was derived from the standard fuel load and associated rate of spread (equation (7.4)) using the current shrub rate of spread model (equation 7.2). The current rate of spread model (equation 7.2) should be regarded as an interim model, since its basis is questionable given the lack (and limited range) of data (Anderson, 2009). The second approach defined the fire danger class boundaries based on the wind speed derived from the standard fuel load and associated rate of spread (equation (7.4)) by solving equation (7.5) for wind speed. Similarly, equation (7.5) is based on a limited dataset (25 observations) and contains a mix of two different fuel types, gorse and manuka/kanuka. Attempts to improve the relationship between rate of spread (r) and ISI using the rate of spread corrected for the various standard fuel loads by equation (7.6) were unsuccessful. A more robust shrub fire rate of spread model would change the boundaries that define the fire danger classes. It is possible that current work to improve the shrub rate of spread model based on fire experiments in manuka fuels in New Zealand will produce an improved rate of spread model (Pearce & Gould, 2005). This work to refine the definition of the fire danger classes should be revisited when an improved rate of spread model is produced.

Changing to three levels of 'Extreme' fire danger for shrub fuels, compared to only one at present is an option, but this might be confusing. These three levels of 'Extreme' fire danger would also not align with the forest and grassland fuel types, with only one 'Extreme' fire danger class. The method of numbered fire danger classes is an alternative approach to describe fire danger in shrub fuels.

Despite previous criticisms from fire management personnel that the current Scrubland Fire Danger Rating model predicts 'Extreme' fire danger too frequently, it has also been recognised that this may be a true indication of the extreme fire potential in shrub fuels (Pearce, 2000a). Results from this thesis have also confirmed that conditions can change rapidly from those that do not support ignition or fire spread to those that can sustain high intensity fires. Therefore the conventional approach to fire danger rating, whereby fire potential gradually increases through fire danger classes, may not be applicable to shrub fuels. It may therefore be better to only describe fire potential in terms of the likelihood of ignition and fire spread. Such an approach could simply describe fire danger in gorse fuels in New Zealand based on the ignition and fire spread thresholds described in Chapter 6 (Table 6.7), without a direct link to fire intensity. This system could also be applied to manuka/kanuka fuels as an interim measure, subject to further validation in these fuels. This approach also has the benefit of aligning with the current five fire danger classes (Table 7.4) and removing the requirement to link with a reliable shrub fire rate of spread model. However, care would be required in the interpretation of these fire danger classes if the nomenclature of 'Low' to 'Extreme' was retained. This system would describe fire danger based on ignition or fire spread potential only and would not be linked to fire intensity, as is the case for forests and grasslands. It may therefore be more appropriate to define the shrub fire danger classes by number, with the 'Low' to 'Extreme' classes used for forest and grassland fuels only.

Table 7.5. Fire danger classes for shrub fuels based on ignition and fire spread thresholds only.

Shrub Fire Danger Class	Fine Fuel Moisture Code	Description of fire potential
1	<69.5	No ignition, no fire spread
2	69.5 - 73.9	Ignitions marginal, no fire spread
3	74.0 – 77.0	Ignition success, no fire spread (individual clumps likely to burn out but no spread across the landscape)
4	77.1 – 82.7	Ignition success, fire spread marginal
5	>82.7	Ignition success, fire spread success

Any proposal to implement changes at the operational level based on outcomes from the work presented in this chapter requires considerable consultation with fire managers. Further discussion around management implications and recommendations are contained in the following chapter.

Chapter 8:
General conclusions and management implications

The work presented in this thesis covered a range of topics relevant to fire in gorse fuels, including fuel-level meteorology, fuel moisture, fire behaviour and fire danger rating. Whilst this work was carried out exclusively in gorse fuels and some results are specific to this fuel type with possible site-specific relationships, the research methodology and broader findings will have applicability to shrub fuels in general. In New Zealand, this work should be extended to include native shrub fuels such as manuka and kanuka. This chapter provides a general summary of the key findings and recommendations for further research to improve the ability to predict fuel moisture, fire behaviour and fire danger in New Zealand shrub fuels. Discussion is also included on the implications for fire management, including considerations for operational implementation of results.

Fuel-level meteorology

The ability to model meteorological conditions under the canopy at the level of the elevated dead fuel is critical for reliable fuel moisture and fire behaviour prediction. Unfortunately, it was not possible to develop reliable models for this purpose. Limited data were available, comprising only two days of meteorological observations from under the gorse canopy. The influence of other processes was also not accounted for in the analyses. These processes included: transpiration from the plants during the day and the effect on relative humidity under the canopy; the trapping of heat and moisture; and the sheltering effect of the canopy that significantly reduced wind speed under the canopy compared to that measured in the open. The models of Byram and Jemison (1943) and Van Wagner (1969) were not suitable to predict fuel-level temperature and relative humidity, since these models base predictions on direct heating of fuels by solar radiation. Little direct solar radiation actually reached the elevated dead fuels under the canopy layer. Regression models did not incorporate the under-canopy physiological and meteorological processes either, as well as other variables that may be important such as canopy roughness, density, distribution of gaps, and vertical structure of the vegetation. Models developed from only two days of data would never be applicable to shrub fuels across the country under all types of weather conditions. However, the findings indicated that there are complex under-canopy processes that influence fuel-level conditions and require further investigation. Further continuous field measurements are required for longer periods of time (weeks or even months) that capture a greater range of weather conditions, variability of fuel characteristics within shrub fuels of the same species, and cover different shrub fuels.

Results indicate that the current system of fire weather reporting and fire danger rating that uses weather inputs from weather stations in open clearings represents fuel-level conditions for shrub fuels inadequately. Conditions under the canopy can be very different to those in the open. This is also a problem for forest fuels, but is unlikely to be significant for grasslands. Grass fuels are more exposed and do not form dense canopies that shelter or alter the microclimate around the main fuel layers responsible for carrying fire. Further research should focus on relationships between weather conditions in the open and those under the shrub canopy. A suitable operational solution would be to apply models that estimate conditions at the fuel level under the canopy from weather station readings in the open. These models would need to account for different shrub types (within and between species) and terrain influences such as slope and aspect.

A further problem is extrapolating weather readings from a single point on the landscape at the weather station across the landscape to apply to shrub fuels many kilometres from the station. Interpolation techniques are currently applied to adjust weather station observations across the landscape between weather stations (Pearce, 2006), but these require further investigation and validation, particularly with regard to rainfall (Tait & Zheng, 2005).

Fuel moisture prediction

The current format of the Fine Fuel Moisture Code (FFMC) from the Fire Weather Index (FWI) System using the FF-scale did not adequately represent actual moisture conditions for the elevated dead fuel layer in gorse. The alternative form of the FFMC, the FX-scale proposed for use in hot and dry climates (Lawson *et al.*, 1996), did not significantly improve the accuracy of the FFMC. This is not surprising, since the FFMC was developed from field data collected in the litter layer of a mature conifer forest (Van Wagner, 1987). The elevated dead layer in gorse is totally different to the litter layer under a mature conifer forest, since the gorse fine fuels are raised above the ground, exposed to air flow and dry much quicker.

An empirical approach adjusted the FFMC to predict the moisture content of the elevated dead layer using regression models following the method of Wotton and Beverly (2007). This provided improved predictive capability over the standard FFMC, but the model fit was still poor. The bookkeeping model that represented a combination of the FFMC and the fuel moisture model of Catchpole *et al.* (2001) provided the best results. This model was able to incorporate fuel-specific response times. The significant inaccuracies of this model were mostly due to the inability to model under-canopy (fuel-level) meteorological conditions.

Response times derived for the elevated dead fuel layer from field data indicated that this layer responded rapidly to changes in the moisture content of the surrounding air. The response time derived from weather observations in the open was 77 minutes.

Accurate modelling of fuel-level meteorological conditions is important for accurate prediction of the moisture content of elevated dead shrub fuels. The bookkeeping model also requires further validation in gorse and extension to manuka and kanuka shrub fuels. More detailed work to determine the response times and fuel-specific coefficients for adsorption and desorption should be carried out under controlled conditions in an environmental chamber (Pippen, 2007). The applicability and relevance of other FWI System codes and indices to shrub fuels requires investigation. Alternative approaches to model fuel moisture, such as physical models that account for moisture transfer and vapour exchanges at the fuel particle level (e.g., Matthews, 2006), can offer significant advantages over the traditional empirical models.

From an operational perspective, the standard system of daily fire danger rating and FWI System calculations may not be appropriate for shrub fuels. The FWI System calculates fuel moisture codes and fire behaviour indices at noon to represent conditions in the mid- to late afternoon period (around 16:00). This is generally regarded as the peak burning period (Van Wagner, 1987; Wotton & Beverly, 2007). The elevated dead fuel layer in gorse responded to atmospheric moisture changes within 2 hours. New Zealand also has a maritime climate with weather conditions that change markedly within hours, unlike the more continental climate of Canada with more predictable daily weather patterns. It is therefore necessary to consider calculating FWI System outputs using hourly weather forecasts, compared to the current system with a single daily calculation at noon. The importance of accurate prediction of FWI System outputs, including hourly calculations, to enhance firefighter safety has been described by Beck *et al.* (2002). A daily display of fire weather outputs could still be provided for general public notification, but based on hourly forecasted weather and not the noon weather observations.

Ignition and fire spread thresholds

The elevated dead fuel layer was the most important layer controlling fire development in gorse fuels. This is significant, since most fire behaviour models assume that surface fuels are the primary carriers of fire spread. The results also contrast with initial findings from fire experiments in manuka shrub fuels in Canterbury, where surface fuels were observed to be critical for fire development and spread (Scion Rural Fire Research, 2008). Wind speed was not a significant variable determining ignition or fire spread success in gorse. This is surprising, since wind speed is expected to be important for fire spread success. However, the data were limited in that it was not possible to undertake experiments under conditions of both high wind and high fuel moisture. Further field experiments are required to extend this work to manuka/kanuka fuels and also to collect a larger range of data that include a combination of high fuel moisture and wind speed.

Despite these limitations, threshold values of fuel moisture developed to determine ignition and fire spread success represent a significant step forward in the understanding of fire development in shrub fuels in New Zealand. Previous estimates of ignition or fire spread thresholds relied largely on either expert opinion or observations from very limited datasets. These experiments have added considerably to this knowledge and provide guidelines to fire managers based on findings derived from actual field experiments. Many previous studies have relied on laboratory experiments under more controlled conditions. The guidelines (Table 6.7) can therefore be used by fire managers to support a range of fire management decision-making activities, such as permit issue for controlled burning, imposition of fire restrictions, and setting fire suppression preparedness and response levels.

Fire danger rating

The current Scrubland Fire Danger Rating model used operationally in New Zealand was evaluated using 25 observations from a broader database of fire behaviour experiments in gorse (9) and manuka/kanuka (16). This current model assumes a standard fuel load of 20 t ha^{-1} across the country for shrub fuels. Observations from the dataset were corrected to represent fire spread and intensity for this standard fuel load, not the actual fuel load consumed for each fire experiment. Different standard fuel loads were assessed to determine the validity of the current 20 t ha^{-1} fuel load assumption. Nearly all of the 25 observations in the dataset had head fire intensities greater than 4000 kW m^{-1}, the current limit for the 'Extreme' fire danger class. The 'Extreme' fire danger class was therefore split into three levels of fire danger. The current model with a 20 t ha^{-1} standard fuel load provided a poor fit to the fire observations, with only 24% of observations classified into the correct fire danger classes. This indicated that the current assumption of a standard shrub fuel load of 20 t ha^{-1} is questionable. The models using standard fuel loads of 30 and 35 t ha^{-1} were better, classifying 80% of observations into the correct fire danger classes in both cases. The model using a fuel load of 30 t ha^{-1} was recommended, since this equates to gorse with a height of 1.5 m and manuka/kanuka with a height of 3.7 m. These revised fuel heights were considered to be more representative of shrub fuel heights across the country than the model using 35 t ha^{-1}.

An alternative approach to define the shrub fire danger classes was developed that used a single value of wind speed to define the boundaries of the fire danger classes. The best models were again those that used standard fuel loads of 30 and 35 t ha^{-1}, with 84% of observations classified into the correct fire danger classes in both cases. The model based on the current standard fuel load of 20 t ha^{-1} only classified 68% of the observations into the correct fire danger classes. Based on fuel height, the model using 30 t ha^{-1} was considered more appropriate than that using 35 t ha^{-1}. However, the wind speed values that defined ‘Extreme’ fire danger were very low – fire danger was predicted to be in ‘Extreme 1’ (representing head fire intensity from 4000-8000 kW m^{-1}) at wind speeds exceeding 1.6 km h^{-1}. The practical relevance of this model is questionable, since under most conditions and on most days of the year fire danger would be predicted to be ‘Extreme’.

For any standard fuel load above 20 t ha^{-1} the ‘Moderate’ fire danger class was absent. This in effect resulted in a ‘step’ being missed, with fire danger progressing from ‘Low’ to ‘High’, instead of from ‘Low’ to ‘Moderate’ and then to ‘High’. In addition, the current fire danger classes are colour-coded for public education purposes. Introducing three levels of ‘Extreme’ could pose a problem, since this is not compatible with the forest and grassland fuel types that only have one level of ‘Extreme’ fire danger. From a practical and public education perspective, this presents a problem with colour coding of fire danger classes (this system would require the use of 7 different colours instead of the current 5). To overcome this issue, an alternative system of numbered fire danger classes from 1 to 6 (Table 7.3) was proposed.

The ignition and fire spread threshold values based on FFMC were also plotted onto the fire danger graphs. The fire behaviour observations fitted these thresholds well, with the majority of the observations (74%) falling above the threshold value for successful fire spread. The fire development thresholds developed in this thesis for gorse fuels may therefore also be applicable to manuka/kanuka fuels, although further validation is required. The FFMC threshold value of 60 for the upper boundary of the ‘Low’ fire danger class (or Class 1 using the alternative classification scheme) was changed to 69.5, representing the boundary between ignition failure and marginal ignition.

In both cases, the fire danger class boundaries were determined using models to predict the rate of spread in shrub fuels. The reliability of the current model (equation 7.2) is questionable, considering the poor model fit and limited observations for Initial Spread Index (ISI) values above 8. The rate of spread model to standardise the fuel load for observations from the fire experiments (equation 7.5) was based on only 25 observations and also represented a mix of gorse and manuka/kanuka. The lack of a reliable rate of spread model for shrub fuels therefore introduced additional error into the definition of the fire danger class boundaries. A reliable rate of spread model for shrub fuels in New Zealand would contribute to a better fire danger rating model.

Further data from both fire experiments and wildfires in shrub fuels are needed to develop an adequate shrub fire danger rating model. Data are particularly lacking at head fire intensities of less than 4000 kW m^{-1}. Reliable models to predict dead fuel moisture content are also critical.

From a fire management perspective, these findings raise significant issues that require further consideration before changes to the current Scrubland Fire Danger Rating model are implemented. Obvious changes could be to modify the standard shrub fuel load to 30 t ha^{-1} and to move the FFMC threshold for the upper boundary of the 'Low' fire danger class from 60 to 69.5. However, bigger questions would remain around defining the fire danger classes and applying the system operationally. This includes the suggestion to change from one level of 'Extreme' fire danger to three and the loss of the 'Moderate' fire danger class. A change to numbered fire danger classes could solve this issue. The alternative fire danger rating model that used wind speed to define the fire danger classes also provided a good fit to the fire observations, but presented a practical problem with the very low threshold of wind speed for 'Extreme' fire danger. Any changes would require a departure from the current system. This could result in difficulties such as maintaining consistency between fuel types and incorporating a shrub fire danger rating system within the current national monitoring system. Given the effort invested to date in developing this system and training fire managers in its use and application, it is preferable to maintain consistency if possible.

Fire danger rating systems are intended to be applied across broad areas or regions to provide a general indication of fire potential and control difficulty. This information is used by fire management agencies for daily and seasonal planning, such as to determine fire season status and conditions for fire permit issue, deliver public education messages, restrict certain activities or access to areas, and manage fire suppression capabilities and readiness. However, the changes required to accommodate an improved shrub fire danger rating system could produce a system that is not compatible with the current national format. Shrub fuels often occur on smaller parcels of land that are distributed across the landscape in patches as opposed to large continuous areas, apart from exceptions such as parts of Northland, East Coast, Central North Island, greater Wellington and Nelson. In addition, it is difficult to model the rapid response of these fuels to changes in atmospheric conditions that affect the moisture content.

An operational approach could therefore be to only use the forest and grassland models for daily fire danger rating purposes across the country. The shrub fire danger rating system could be excluded from public display or access, but used to implement fire management activities for shrub-dominated areas. This would use either of the two models from Chapter 7:

1. Model 1 (Figure 7.9) – standard fuel load 30 t ha^{-1}; fire danger classes either from 'Low' to 'Extreme 3' (with no 'Moderate' class) or numbered from 1 to 6; threshold between 'Low/Class 1' and 'High/Class 2' based on an FFMC value of 69.5; fire danger class boundaries defined by FFMC and variable wind speed values.
2. Model 2 (Figure 7.10) – standard fuel load 30 t ha^{-1}; fire danger classes either from 'Low' to 'Extreme 3' (with no 'Moderate' class) or numbered from 1 to 6; threshold between 'Low/Class 1' and 'High/Class 2' based on an FFMC value of 69.5; fire danger class boundaries defined by a single wind speed value.

Another approach could be to base shrub fire danger classes solely on the FFMC threshold values that define ignition and fire spread success (Chapter 6 and Table 6.7). This system would produce five numbered fire danger classes that relate to ignition or fire spread success (Table 7.5). Fire management strategies and tactics would then be based on these indicators of fire potential. Such a system could have merit if the nature of fire behaviour in shrub fuels is considered. Fire potential in shrub fuels is very different to that in forests and grasslands. Shrub fuels are capable of extreme intensity and fire behaviour under conditions where fires can fail to develop or pose any serious threat in other fuel types, particularly forests. Fires will often either fail to develop and spread in shrub fuels, or conversely will develop rapidly into fast-spreading fires with head fire intensities well in excess of 4000 kW m^{-1}, the upper level of suppression effectiveness on a head fire. A 'conventional' fire danger rating system with stepped classes of fire danger from low intensity through to extreme is therefore perhaps not applicable for shrub fuels. The only possible alternative is to then base descriptions of fire potential on whether fires will develop or not.

These findings and discussion raise significant issues that require thoughtful analysis by fire managers and scientists before significant changes can be made. A significant change to a completely different system after an extended period of research and validation may be more appropriate than numerous small incremental changes with potential for confusion on each occasion. It is therefore recommended that prior to any changes being implemented to the current Scrubland Fire Danger Rating Model, extensive consultation with a range of fire managers takes place.

Key recommendations

The work presented in this thesis has highlighted areas that require further research and implications for fire management that require consideration prior to any operational implementation of the research results. Key research recommendations are:

- Extend the work presented in this thesis to a broader range of gorse sites, and also to native shrub fuels, particularly manuka and kanuka.
- Develop models that predict fuel-level conditions from weather observations collected in the open at standard weather stations.
- Determine the response times for shrub fuels more accurately from laboratory experiments in a controlled environmental chamber.
- Undertake more extensive field validation of the bookkeeping approach for fuel moisture prediction, and also extend it other shrub fuels.
- Develop a robust rate of spread model for New Zealand shrub fuels.
- Collect more fire behaviour data from both experimental fires and wildfires, under targeted conditions of head fire intensity, wind speed and fuel moisture. Data of wildfire suppression effectiveness would also be useful to validate the fire danger rating system classes for shrub fuels.

Key fire management considerations are:

- Select the most appropriate system for fire danger rating in shrub fuels to support fire management decision-making and to suit public education and awareness purposes.
- Should an alternative model result in a system that is not compatible with the current national fire danger monitoring system, a new system may need to be developed.
- Change the current fire danger rating system from a single daily noon calculation of FWI System codes and indices to hourly prediction to present more accurate fire danger information for fast-responding shrub fuels, or as a minimum base the noon daily calculation on continuous hourly weather observations rather than once-per-day observations.

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