Development of a model system to predict wildfire behaviour in pine plantations[1]

Miguel G. Cruz[1,4], Martin E. Alexander[2] and Paulo A.M. Fernandes[3]

[1]Bushfire Dynamics and Applications, CSIRO Forest Biosciences, PO Box E4008, Kingston, ACT 2604, Australia
[1]Bushfire Cooperative Research Centre, Melbourne, Victoria, Australia
[2]Canadian Forest Service, Northern Forestry Centre 5320-122 Street, Edmonton, Alberta T6H 3S5, Canada
[3]Centro de Estudos em Gestão de Ecossistemas & Departamento Florestal, Universidade de Trás-os-Montes e Alto Douro, Apartado 1013, 5001-801 Vila Real, Portugal
[4]Email: miguel.cruz@csiro.au

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Summary

We describe the development of a model system to predict fire behaviour over the full range of potential fire behaviour in the various types of fuel complexes found in exotic pine plantations in relation to environmental conditions. The proposed system integrates a series of sub-models describing surface fire characteristics and crown fire potential (e.g. onset of crowning, type of crown fire and associated rate of spread). The main inputs are wind speed, fine dead fuel moisture content and fuel complex structure (surface fuel bed characteristics, canopy base height and canopy bulk density). The detail with which the model system treats surface and crown fire behaviour allows users to quantify stand 'flammability' with stand age for particular silvicultural prescriptions.

The application of the model to a case study of thinning treatments in a radiata pine plantation in Victoria is presented. The results highlight the complex interactions that take place between fire behaviour and attendant fuel and weather conditions. Structural changes in the fuel complex introduced by the treatments altered fire behaviour, but no definite reduction and or increase in rate of fire spread was identified. The results illustrate the role that simulation models can play in support of silvicultural and fuel management decision making.

Keywords: fire behaviour; spread; plantations; models; fuels; environmental factors; management; silviculture; characteristics; radiata pine

Introduction

The ability to predict fire behaviour (e.g. spread rate and intensity) in relation to the fire environment is fundamental to safe and effective fire management decision-making (Countryman 1972). Examples of applications include prescribed fire use planning and execution, support of wildfire suppression strategies and tactics, and gauging fuel management effectiveness. Models used to evaluate fuel treatments should be sensitive enough to detect the effects of changes in fuel complex structure and composition (e.g. surface fuel load or canopy base height) on the 'flammability' or general fire potential of a forest stand (Bilgili 2003). Such models would explicitly allow one to translate physical fuel characteristics to various fire behaviour outputs, thereby quantifying the variation in fire hazard with stand age for particular silvicultural prescriptions (Alexander 2007). It would also allow for the determination through 'what-if' analyses of the optimal level and timing of fuel treatments associated with a pre-defined degree of allowable wildfire risk.

The growth characteristics and silvicultural systems that characterise pine plantations established on productive sites result in fuel complexes that can be exceptionally flammable (Williams 1976) but at the same time are amenable to fuel modification. Sometime after canopy closure, the relatively high canopy biomass coupled with the existence of ladder fuels (e.g. dead bole branches and dead, suspended needles) and the surface fuel accumulation rates lead to the formation of fuel complexes capable of sustaining the propagation of high-intensity crown fires (Douglas 1964; McArthur 1965) and other extraordinary fire phenomena (Sutton 1984). By breaking both the vertical and horizontal fuel continuity, silvicultural interventions can modify the fuel complex structure into a less flammable one. An adequate treatment would modify canopy structure (e.g. increase canopy base height and reduce canopy bulk density), hence limiting the potential for the onset and subsequent development of high-intensity crown fires.

In Australasia, three distinct systems are used to predict wildfire behaviour in pine plantations: the McArthur Forest Fire Danger Meter (McArthur 1967; Noble *et al.* 1980) in South and eastern Australia, the Forest Fire Behaviour Tables (FFBT) in Western Australia (Sneeuwjagt and Peet 1985; Beck 1995) and the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992; Taylor *et al.* 1997; Wotton *et al.* 2008) adopted by New Zealand (Pearce and Anderson 2008). While some limited testing has been undertaken (McArthur 1965; Cheney 1968; Fogarty *et al.* 1996; Alexander 1998; Burrows *et al.* 2000; Cruz and Plucinski 2007), none of these systems has been developed or extensively evaluated for application to wildfires in Australasian exotic pine plantations burning under

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severe weather conditions. Pearce and Alexander (1994) have, however, qualitatively evaluated the New Zealand forest fire danger classification scheme (Alexander 1994), which is based on the FBP System, against several major wildfire incidents. These three systems are known to produce quite different results in terms of rate of fire spread for the same environmental conditions (Cheney 1991; Cruz and Fernandes 2008).

Furthermore, none of these systems are able to answer questions related to the effects of stand structure, silvicultural operations and or fuel treatments with respect to influencing fire behaviour potential in exotic pine plantations. Evidence gathered from wildfire case studies in Australasian pine plantations (Prior 1958; Douglas 1967, 1974a; Ollerenshaw and Douglas 1971; Geddes and Pfeiffer 1981; Keeves and Douglas 1983; Watson *et al.* 1983) supports the idea that some fuel complex structures are exceptionally flammable, which in turn allows for high-intensity fire spread under even moderate burning conditions, whereas other configurations will retard a fire's rate of spread and intensity under similar fire weather situations. Billing (1983), for example, observed high-intensity crowning in young pine plantations at McArthur (1967) Forest Fire Danger Index (FFDI) levels of 6 to 7. From an analysis of fire spread on three Australian wildfires, McArthur (1965) suggested that under high fire danger conditions — that is, an FFDI between 25 and 50 — fires spreading in young unthinned and unpruned radiata pine (*Pinus radiata* D.Don) plantations had rates of advance two to three times faster than in pruned and thinned maritime pine (*Pinus pinaster* Ait.) stands. Billing (1980) reported similar evidence for the Caroline Fire in South Australia, where under high to very high fire danger, unthinned unpruned radiata pine stands sustained passive crown fire propagation while fire spread in treated stands was characterised by low-intensity surface fire spread. Billing (1980) also indicated that under extreme fire danger ratings, that is FFDI 50–60, thinned stands burned as severely as neighbouring unthinned ones.

Two more recent wildfires, the 1994 Gnangara wildfire in 30–40-y-old maritime pine plantation stands in Western Australia (Burrows *et al.* 2000) and the 1991 Toolara No. 7 wildfire (Alexander 1998) in 20-y-old slash pine (*Pinus elliottii* E.) plantation stands in south-eastern Queensland, provide evidence of moderated fire activity in mature pine plantations under very high fire danger conditions (FFDI 25–50). In both instances, fire spread occurred through an array of mature stands submitted to a range of silvicultural and surface fuel treatments. The Gnangara wildfire spread mostly as a high-intensity surface fire, with occasional sustained crown fire propagation in denser stands. Nevertheless, stand structure, namely high canopy base heights, limited the propensity for crowning. Similarly, the Toolara No. 7 wildfire propagated mostly as a surface fire with periodic episodes of crown fire activity. Alexander (1998) considered that the silvicultural history of the 20-y-old slash pine plantation stands created a fuel type that prevented the development of an active crown fire under very high fire danger conditions. Periodic bursts of crown fire activity associated with certain fuel structures and occasional strong wind gusts tended to be short lived because the overall stand structure did not provide the continuity in fuel arrangement (both vertically and horizontally) that would allow for the maintenance of a continuous, fully developed crown fire.

The objective of this paper is to describe the development of a model system aimed at predicting the rate of spread and other associated fire behaviour characteristics in pine plantations. The following attributes for the model system were considered desirable: (1) applicability over the full spectrum of fire behaviour (i.e. from low-intensity surface fires to fully-developed, high-intensity crown fires); (2) explicit inclusion of the effects of relevant fuel complex variables determining the start and spread of crown fires; and (3) adequate quantitative description of fire behaviour factors and processes determining crown fire propagation. The linkages between the various model components are described and a detailed case study application is presented to illustrate the model system's capabilities.

Methods

Model structure

The proposed model system — Pine Plantation Pyrometrics (hereafter referred to as PPPY) — aims to predict the rate of spread and type of fire over the full range of fire behaviour for a variety of fuel complex structures in relation to wind and fuel moisture conditions. The system encompasses a suite of fire environment and fire behaviour models that describe the relevant processes occurring within and above a spreading fire. PPPY distinguishes three modes of fire spread: surface fire, passive crown fire and active crown fire. In order to do this, the system relies on three core models: one for predicting the spread rate of a surface fire, a second one for assessing the onset of crowning, and finally a model predicting the type of crown fire and its associated spread rate.

The concept of passive and active crown fire regimes was first introduced by Van Wagner (1977). A crown fire spreading in the active regime is characterised by a solid and continuous flame front encompassing both surface and canopy fuel layers. The rate of spread is determined by the crown phase although the steady-state rate of spread is dependent on the heat released by the surface fire. In a passive crown fire, also called an intermittent crown fire (Douglas 1964; Forestry Canada Fire Danger Group 1992), the crown phase is directly dependent on the surface fire and the rate of spread is somehow determined by the surface phase. The passive regime covers a range in fire behaviour that spans from the ignition of groups of trees behind the leading edge of the flame front through to the transition to active crowning. In the mid-range of this spectrum, a passive crown fire is characterised by a broken or discontinuous flame sheet extending from the surface fuels to the canopy fuel layer.

Within the system, the spread of surface fires is the most critical component. Surface fire rate of spread typically varies over two orders of magnitude (e.g. 6–600 m h^{-1} or 0.1 to 10 m min^{-1}) and is a major determinant of crowning potential. While some of the models or guides mentioned earlier were specifically developed to predict surface fire spread in exotic pine plantations, such as the FFBT and FBP System fuel type C-6 (conifer plantation), we decided to use the Rothermel (1972) fire spread model with customised fuel models developed for maritime pine plantation stands (Cruz and Fernandes 2008). This choice is supported by the comparative analysis of the above-mentioned surface fire spread models (see Cruz and Fernandes 2008). The other two core models used were the Cruz *et al.* (2006a) crown fuel ignition model to predict the onset of crowning coupled with Van Wagner's (1977) criteria for active crowning and the Cruz *et al.* (2005) models for predicting the type of crown fire and its associated spread rate (Fig. 1). The system includes other models that are required to produce inputs to aforementioned core fire behaviour models. These intermediate quantities or outputs include the fireline intensity (Byram 1959), flame height (Albini 1981), reaction or flame front residence time (Nelson 2003b), and the convection column or plume structure characteristics (Mercer and Weber 1994) of surface fires. Given the nature of the models that comprise PPPY, the model system can be classified as a hybrid between an empirical and a physical model. The physical components deal mainly with heat transfer (Cruz *et al.* 2006a) and fluid flow (Mercer and Weber 1994; Nelson 2003a) and are used in the modelling of crown fire initiation. The empirical component deals principally with the development of fuel models associated with the Rothermel (1972) surface fire rate of spread model and the prediction of crown fire rates of spread according to the Cruz *et al.* (2005) models. The range in empirical data on rate of fire spread and fuel consumption in relation to various fireline intensity levels incorporated into the models to predict these two aspects of fire propagation is presented in Figure 2.

The primary inputs into the PPPY model system (Table 1) are:

- wind speed (10-m open standard or within stand)
- weather variables (i.e. temperature, relative humidity, cloud cover) determining the fine dead fuel moisture content as per Rothermel (1983)
- surface fuel load and depth
- surface fuel model (Cruz and Fernandes 2008)
- fuel strata gap (i.e. the distance between the surface fuel layer and the bottom of the canopy layer) as defined by Cruz *et al.* (2004)
- canopy bulk density.

There is a set of inputs that can be seen as secondary due to their minor effect on the model system (e.g. stand density and basal area, live foliar moisture content). The system can provide simulations relying on assumed averaged input values for these secondary inputs (Cruz *et al.* 2006b), although the use of measured or estimated values will reduce the uncertainty in the resultant outputs.

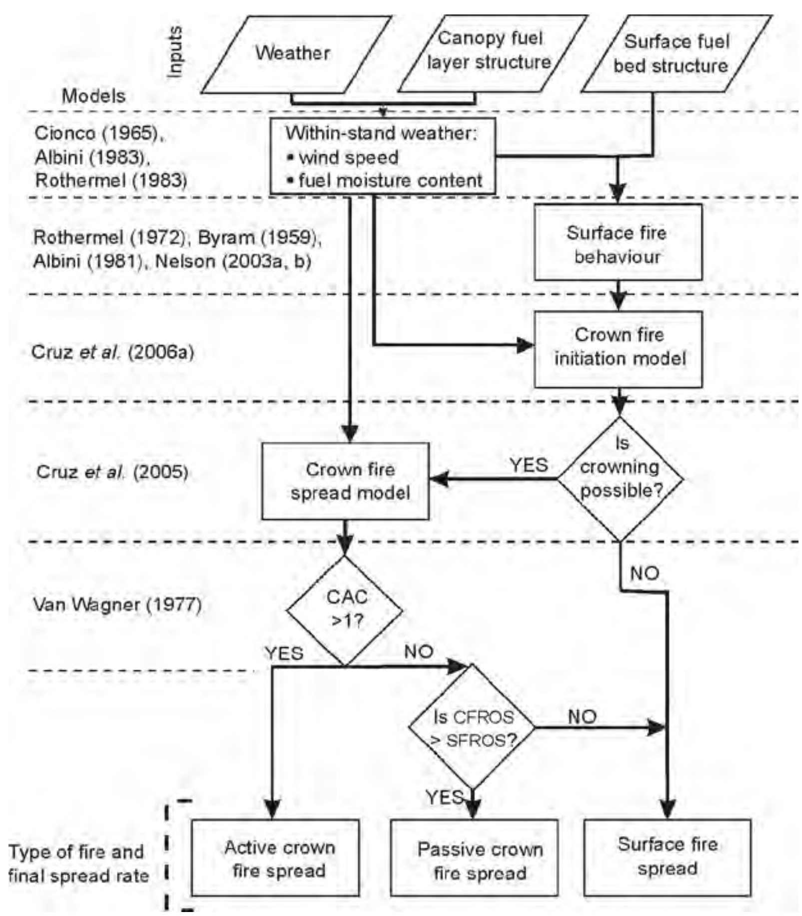

Figure 1. Flow diagram of the PPPY model system for predicting fire behaviour in pine plantations (after Cruz *et al.* 2006c). CAC is the criteria for active crowning (Van Wagner 1977), CFROS the crown fire rate of spread and SFROS the surface fire rate of spread.

Table 1. The main fuel and weather input variables required to run the PPPY model system

Variable	Units	Period of change[A]
Fuel complex		
Fine dead fuel moisture content[B]	% oven-dry weight	Very short
Live foliar moisture content	% oven-dry weight	Medium
Available surface fuel load[C]	kg m^{-2}	Medium/long
Surface fuel layer depth	m	Medium/long
Fuel strata gap	m	Long
Surface fuel model	–	Long
Canopy bulk density	kg m^{-3}	Long
Stand height	m	Long
Stand density	trees ha^{-1}	Long
Fire weather		
Wind velocity	km h^{-1}	Very short
Air temperature	°C	Very short

[A]Very short = minutes or hours; medium = months; and long = years
[B]As it pertains to the surface needle litter layer, as opposed to ladder or aerial fuels
[C]Within the present analysis available, surface fuel load corresponds to the fuels typically consumed in flaming combustion, namely needle litter and small twigs <6 mm in diameter (Luke and McArthur 1978)

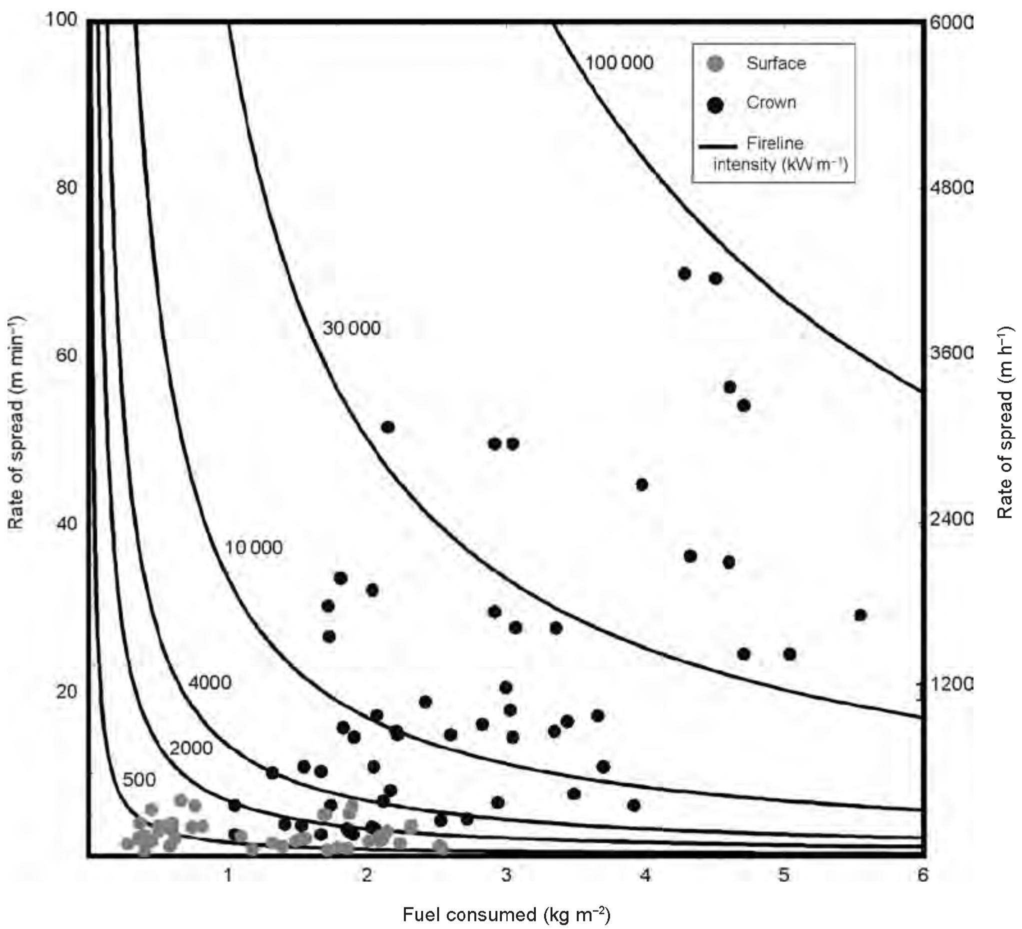

Figure 2. Head fire rate of spread and fuel consumed in relation to the type of fire and six distinct levels of Byram's (1959) fireline intensity (kW m^{-1}), assuming a heat of combustion of 18 000 kJ kg^{-1}, for the experimental surface and crown fires used in the development of the fire spread functions included within the PPPY model system for predicting fire behaviour in pine plantations

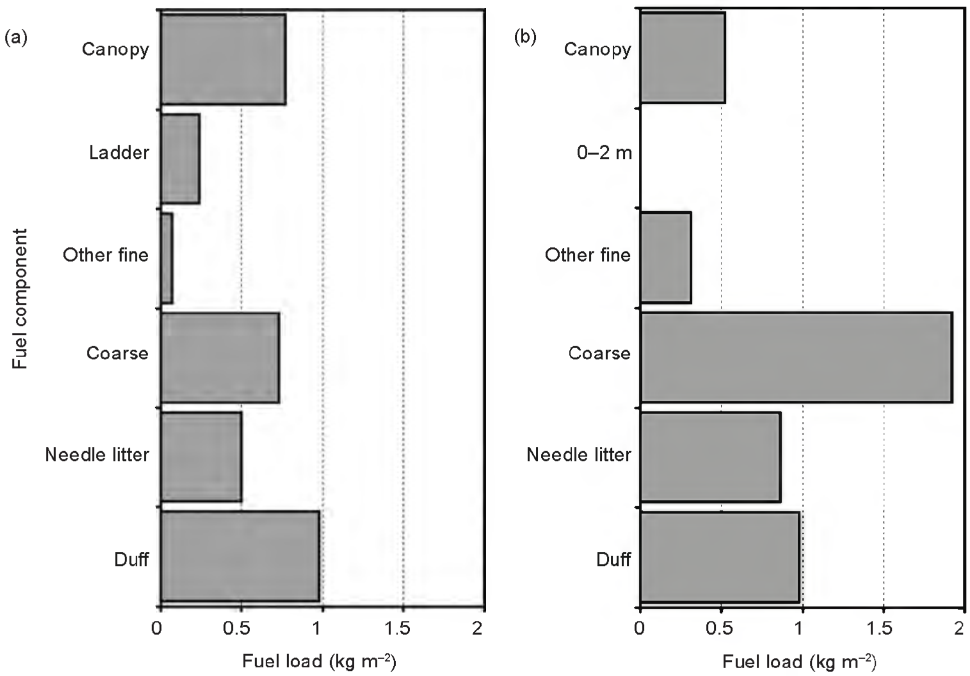

Figure 3. Fuel load distribution per fuel complex component (a) before and (b) after treatment (thinning with 50% reduction in basal area) of a 12-y-old radiata pine plantation (after Williams 1978)

The final outputs of the PPPY model system are the type of fire and the associated rate of spread of the head fire. It is anticipated that additional models for predicting crown scorch heights, maximum spotting distances and sizes of fire-fighter safety zone, for example, will be added to the system at a later date to answer specific management questions. Alternative input processing models may also be considered for fuel moisture (e.g. Pook 1993; Pook and Gill 1993). Similarly, a dynamic fuel complex model like that of Bilgili and Methven (1994) might also be developed as an adjunct to PPPY.

From the physical description of the fuel complex and wind conditions, the system determines the vertical wind profile within the stand (Cionco 1965; Albini 1983). From the vertical wind profile and an estimate of fine dead fuel moisture content, the surface fire rate of spread and other characteristics (i.e. residence time, flame depth and height) are calculated. These predicted quantities along with fuel strata gap are used to determine whether the surface fire is likely to ignite canopy fuels. If crowning is considered possible, the system calculates the expected active crown fire spread rate ($CFROS_A$) from the Cruz *et al.* (2005) model. Taking into account the Van Wagner (1977) criteria for active crowning (CAC), a determination is made as to whether the crown fire is spreading in a passive or active mode based on the canopy bulk density (CBD, kg m^{-3}) as per Van Wagner (1977):

$$CAC = \frac{CFROS_A}{S_o/CBD} \quad (1)$$

where S_o is the critical mass flow rate for solid crown flame. Currently, the best available estimate of S_o for conifer forest stands is 180 kg m^{-2} h^{-1} or 3.0 when $CFROS_A$ is expressed in m h^{-1} or m min^{-1}, respectively. If the CAC is greater than 1.0, it is considered that the fire is spreading as an active crown fire as per the rate given by the Cruz *et al.* (2005) model. If the fire is considered a passive crown fire (i.e. CAC <1.0), then there is a need to verify whether the predicted passive crown fire spread rate (Cruz *et al.* 2005) is higher than the predicted surface fire rate of spread, the highest value being the simulation output.

Case study simulation

To help illustrate the value of PPPY, the model system was used to simulate potential fire behaviour in two structurally different radiata pine stands. Williams (1978) analysed the effect of four different commercial thinning regimes on the fuel complex of a 12-y-old radiata pine plantation. The author quantified the pre- and post-treatment fuel complex structure, namely surface fuel load by roundwood diameter size classes, fuel strata gap, and canopy fuel load (Fig. 3). The pre-treatment stand had a density of 1400 trees ha^{-1}, a top height of 16.6 m and a basal area of 27.5 m^2 ha^{-1}.

The prediction of rate of spread and type of fire in relation to fuel and weather conditions for the stands sampled by Williams (1978) allows one to identify the impact of thinning treatment on potential fire behaviour. The fuel complex characteristics for the unthinned and thinned (50% reduction in basal area) stands were respectively:

- surface fuel available for combustion — 0.5 and 1.1 kg m^{-2}
- fuel strata gap — 0.9 and 1.7 m
- canopy bulk density — 0.1 and 0.05 kg m^{-3}.

It is expected that within a thinned stand the changes in microclimate characteristics (e.g. wind and fuel moisture) will result in a drier surface fuel layer than what would be found in

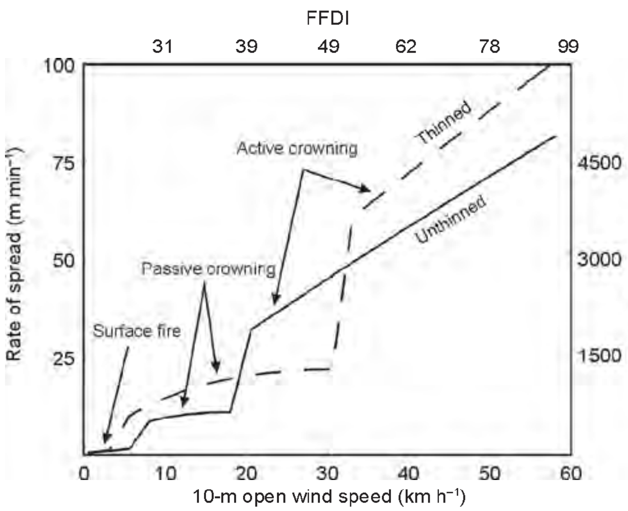

Figure 4. Head fire spread rate as a function of open wind speed for 12-y-old unthinned and thinned (50% reduction in basal area treatment) radiata pine plantation stands as per Williams (1978) (after Cruz *et al.* 2006c). The McArthur (1967) Forest Fire Danger Index (FFDI) calculations are based on an air temperature of 40°C, relative humidity of 20% and a Drought Factor of 10 (Noble *et al.* 1980).

the pre-treatment condition. For these simulations we estimated fine dead fuel moisture content by applying Rothermel (1983) fuel moisture tables to the unthinned (assuming canopy cover >50%) and thinned (canopy cover <50%) radiata pine stands using an air temperature of 40°C and relative humidity of 20%. This resulted in a fine dead fuel moisture content of 7% in the untreated stand and 5% in the treated area. Live foliar moisture content was assumed to be 100% (Pook and Gill 1993). Surface fire rate of spread was based on the fuel-type-specific models developed by Cruz and Fernandes (2008).

Results and discussion

Although Williams (1978) provided an accurate description of the physical fuel variables influencing fire behaviour he was unable to quantify the fuel hazard associated with each thinning regime. As he states, 'A discussion of the effect of thinning on fire behaviour must, at this stage of our knowledge, be qualitative.' His main doubts related to how the rearrangement of the fuel complex —a reduction in crown fuel quantity, an increase in fuel strata gap, an increase in surface fuel load, and changes in the stand microclimate (Pook and Gill 1993) — would affect the overall fire spread and intensity potential.

The results of the simulation presented in Figure 4 show that although the changes introduced by the treatment do alter potential fire behaviour, no definitive trend (reduction or increase) in the rate of fire spread could be identified. The thinning resulted in an increase in the potential rate of fire spread for low and high wind speeds as measured in the open at a height of 10 m (U_{10}), while the unthinned stand showed higher potential rate of spread within the range 20 to 30 km h^{-1}. The model system was able to identify the effect that the changes in various properties of the fuel complex had on the overall rate of fire spread and to identify the thresholds for crowning activity. More importantly, the system quantified the sudden jumps or increases in the rate of fire spread associated with the transitions from a surface fire to the onset of crowning and from passive to active crown fire development. For wind speeds <20 km h^{-1} the increase in surface fuel load and reduction in fine dead fuel moisture content due to the thinning resulted in crowning occurring under milder conditions than was the case with the unthinned stand, although the reduction in canopy bulk density limited the spread regime to passive crowning. The unthinned stand reached the threshold for active crowning at $U_{10} \sim 20$ km h^{-1}, and within the 20–30 km h^{-1} interval this fuel complex had the higher potential spread rate. Once $U_{10} > 30$ km h^{-1}, the conditions for active crown fire propagation were met for the thinned stand and its drier surface fuel condition resulted in higher rates of spread.

The sudden jumps in fire rate of spread as illustrated in Figure 4 are due to a change in the 'drivers' of the fire propagation process. From a theoretical point of view, a fire spreads at a steady state in equilibrium with a set of environment variables. Any changes in one of the determining variables (e.g. increase in wind speed or slope, or decrease in fine fuel moisture) can induce the involvement of additional fuel layers and consequently a new dynamic fire state (Cheney and Gould 1997). An obvious example is the transition from a surface fire to a crown fire. Within a pine plantation, surface fire rate of spread is a function of the litter layer characteristics, including fuel load, compactness and moisture content, and within-stand wind speed. After crowning, the flame front is subject to stronger winds (typically at least 3–5 times higher), there is a considerable increase in the amount of fuel consumed in flaming combustion, and the fire is spreading on a fuel stratum characterised by higher heat transfer efficiency (Alexander 1998). The steady-state rate of spread in this new situation can be several times higher than that observed prior to crowning. Scott (2006) regarded such abrupt changes in spread rate as wind speed increases as 'curious' and that such predicted behaviour was an artefact of any crown fire modelling system. However, abrupt changes in rate of spread after crowning by prescribed, experimental and wild fires are well documented (e.g. McArthur 1965). For example, while observing the behaviour of a series of experimental fires in a maritime pine plantation in Western Australia, Burrows *et al.* (1988a) noted that when crowning did occur, rates of spread were 2–5 times greater than those of surface fires. Similarly, during an experimental burning study in maritime pine in Portugal, Fernandes *et al.* (2004) documented a near two-fold increase in rate of spread between a plot experiencing a high-intensity surface fire with individual tree torching and a plot where crowning was continuous.

The identification of transition points between the different types of fire propagation is particularly significant to fire operations and fire-fighter safety (Douglas 1974b; Forest Fire Management Group 2007). The increases in rate of spread and intensity that characterise transitions in fire behaviour levels can limit direct suppression action and can put fire-fighters in a precarious situation (Douglas 1964; McArthur *et al.* 1966).

The simulation presented in Figure 4 indicates that the silvicultural treatment described by Williams (1978) did not attain its intended purpose of reducing the fire hazard associated with the structure of the fuel complex. Several issues are worth discussing. From Williams' (1978) description, the thinning operation did not alter the vertical fuel continuity sufficiently, and the retention of the thinning debris led to a more flammable surface fuel layer. The PPPY model system results point out that for this particular stand, further fuel modification (e.g. low pruning and or surface fuel reduction or removal) would be necessary to achieve a definitive reduction in fire potential. It is also worth noting the relatively short-term duration of the negative effects of the silvicultural treatment on potential fire behaviour. A thinning operation will affect the surface fuel bed structure and composition by increasing fuel loads and producing a more aerated fuel bed structure, while at the same time inducing a drier within-stand microclimate (Williams 1977; Woodman 1982; Pook 1993) and allowing higher within-stand wind speeds as a result of the reduction in stand basal area (Cooper 1965). With time, the overstorey canopy gaps will close and decomposition and compaction of thinning slash residues will bring the surface fuel layer to a state similar to the pretreatment one. The time required for the fuel complex to reach this state depends on various factors. The nature and intensity of the thinning operation will determine the characteristics and amount of biomass added to the surface fuel layer, and the density of the post-treatment stand. Pre-treatment stand condition (e.g. vigour of residual trees) and site productivity will determine the response of the standing trees to the newly created growing space and the time required to reoccupy the available canopy space (Madgwick 1994). Site characteristics and climate will also determine the time required to transform the flashy fuels contributed by the thinning operation into an amorphous and compacted layer with a relatively small effect on the potential rate of fire spread (Woodman and Rawson 1982).

The results of the case study simulation carried out here emphasise the complexities associated with analysing the effectiveness of fuel treatments on potential fire behaviour. Changes in fuel complex structure that arise from certain silvicultural and fuel treatments are difficult to interpret in terms of the resulting fire behaviour because of the influence that these changes have on the fire environment which in turn affect the different phenomena driving fire behaviour. For a given fuel structure, such as the thinned stand described by Williams (1978), the variation in fuel availability that occurs throughout a fire season, the interaction between distinct combusting fuel strata, and the complexity and dominance of certain heat transfer processes over others, makes it difficult to quantify stand flammability from a description of the fuel complex alone.

Concluding remarks

PPPY is a model system that integrates a number of models aimed at predicting fire behaviour in pine plantation stands. In this paper we have not provided a direct evaluation of the system's overall performance. However, its main components, namely the models describing surface fire spread, onset of crowning and crown fire propagation have been evaluated against independent datasets (e.g. Hough and Albini 1978; Cruz *et al.* 2005, 2006b; Alexander and Cruz 2006; Cruz and Fernandes 2008). The evaluations carried out gave acceptable results, although the surface fire rate of spread model was found to underestimate fires burning under marginal burning conditions, namely for fine dead fuel moisture contents > 25%.

We have also not compared the predictions of the PPPY model system with those of other model systems designed to predict fire behaviour in pine plantations, such as the conifer plantation (C-6) fuel type model of the Canadian FBP System or the pine plantation models found in the Western Australian FFBT guide. The thoroughness with which the PPPY model system considers the processes involved in fire behaviour can presumably better identify the responses to changes in fuel and weather characteristics than these other models, especially for moderate to extreme burning conditions. We have found that for conditions typical of prescribed burning in pine plantations (e.g. light fuel loads, high fuel moisture contents and merging flame fronts from strip head fires or point source ignitions), the PPPY model system may not be applicable. In such cases, guides specifically designed for prescribed burning are far superior (e.g. Billing 1979; Byrne 1980; Woodman and Rawson 1982; Hunt and Crock 1987; Burrows *et al.* 1988b, 1989; Fernandes *et al.* 2008).

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