Development Of A Model System To Predict Wildfire Behaviour In Pine Plantations

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Abstract

We describe the development of a model system for the prediction over the full range in fire behaviour in exotic pine plantation fuel types in relation to environmental conditions. The proposed system integrates a series of sub-models describing surface fire characteristics and crowning potential properties (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, namely 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 radiata pine plantation thinning treatment case study in Victoria is presented. The results highlight the complex interactions that take place between fire behaviour and attendant fuel and weather conditions. The structural changes introduced in the fuel complex by the treatment 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: Onset of crowning, crown fire spread modelling, fuel management, rate of fire spread.

Introduction

The ability to predict fire behaviour (e.g., spread rate and intensity) in relation to the fire environment is fundamental to 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. Such models would 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. It would also allows 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 characterize pine plantations established on productive sites result in fuel complexes that can be exceptionally flammable 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 surface fuel accumulation rates lead to the formation of fuel complexes capable of sustaining crown fire propagation under moderate burning conditions (McArthur 1965). By breaking both the vertical and horizontal fuel structures, 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 possibility 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) adopted by New Zealand (Pearce and Anderson 2007). While some limited testing has been undertaken (McArthur 1965, Fogarty et al. 1996, Alexander 1998, Burrows et al. 2000), none of these systems have been developed or extensively evaluated for application to wildfires in Australasian exotic pine plantations burning under severe weather conditions. Pearce and Alexander (1994) have, however, qualitatively evaluated the New Zealand forest fire danger classification scheme, 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, in review). Furthermore, none of these systems are able to answer questions related to the effects of silvicultural operations and/or fuel treatments with respect to influencing fire behaviour potential in exotic pine plantations.

The objective of this paper is to describe the initial work on 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 gentle 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 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. 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 be able 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 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 characterized by a solid and continuous flame front encompassing the 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 of fire behaviour that spans from the ignition of isolated or groups of trees behind the leading edge of the flame front to the onset of active crowning. In the mid range of this spectrum, a passive crown fire is characterized 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 three orders of magnitude (e.g., 6 to 600 m/h or 0.1 to 10 m/min) 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 customized fuel models developed for maritime pine (*Pinus pinaster* Ait.) plantations (Cruz and Fernandes in review). This choice is supported by the comparative analysis of the above mentioned surface fire spread models (see Cruz and Fernandes in review). 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 (Figure 1). The system includes other models that are required to produce inputs to aforementioned core fire behaviour models. These intermediate quantities include fireline intensity (Byram 1959), flame height (Albini 1981), reaction time (Nelson 2003b), and convection plume structure (Mercer and Weber 1994).

The primary inputs into PPPY are: wind speed (10-m open standard or with-in stand), weather variables determining dead fuel moisture content (i.e., temperature, relative humidity, cloud cover), surface fuel load and depth, surface fuel model (Cruz and Fernandes in review), fuel strata gap (i.e., the distance between the surface fuel layer and the bottom of the canopy layer; Cruz et al. 2004), and canopy bulk density (Table 1). 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, 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.

The final output of the PPPY system are the type of fire and the associated head fire rate of spread. It is anticipated that additional models for predicting crown scorch height, maximum spotting distances, and fire-fighter safety zone sizes, for example, will be added to the system at a later date to answer specific management questions as well as additional features (e.g., mechanical effect of slope steepness on rate of fire spread).

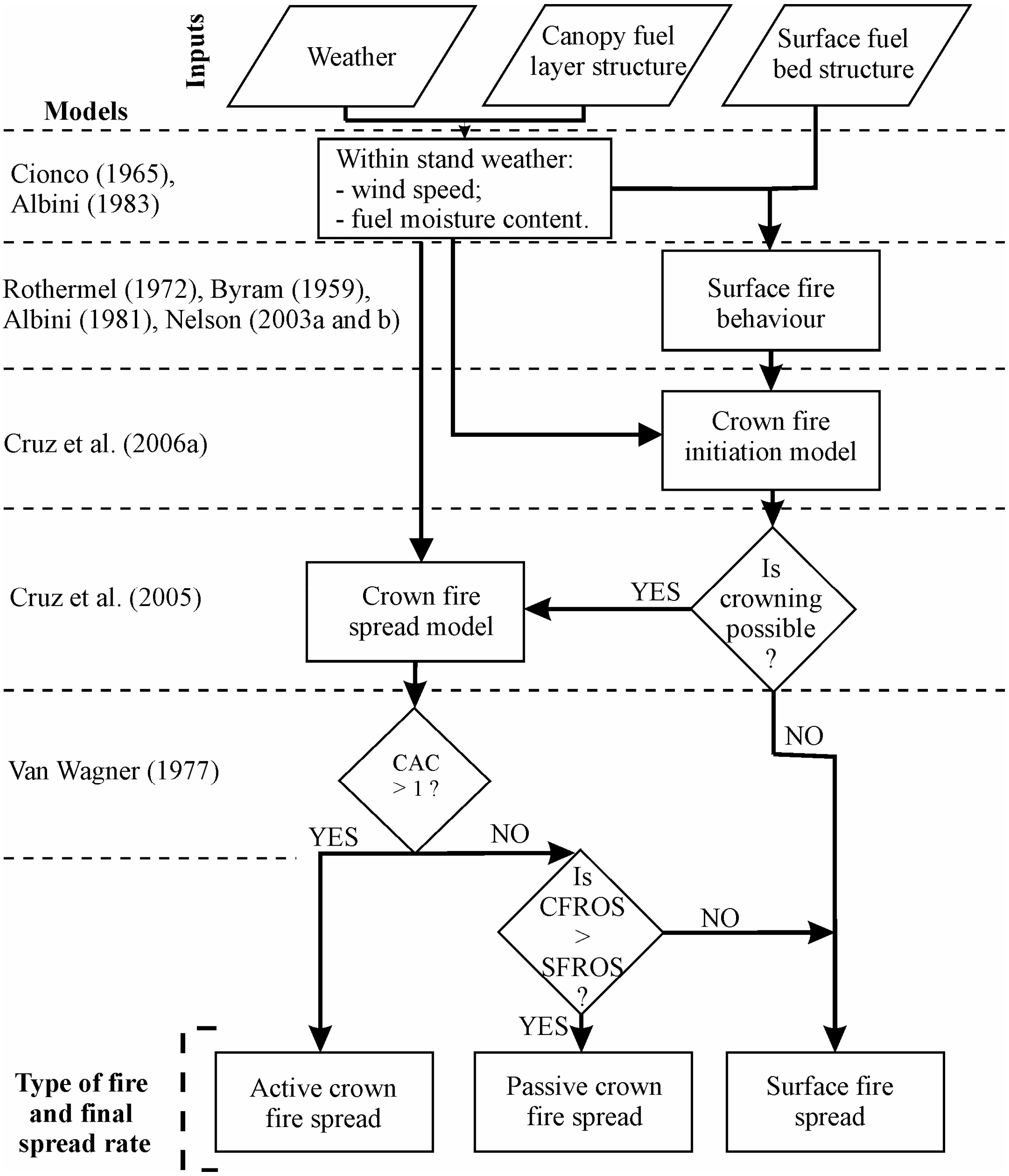

Figure 1. Flow diagram of the PPPY model system for predicting fire behaviour in pine plantations (after Cruz et al. (2006c). CAC is the criteria for active crowning (Van Wagner 1977), CFROS is the crown fire rate of spread, and SFROS the surface fire rate of spread.

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 if the surface fire is likely to ignite canopy fuels. If crowning is considered possible, the system calculates the expected active crown fire spread rate ($\mathrm{CFROS_A}$) from the Cruz et al. (2005) model. Taking into account the Van Wagner (1977) criteria for active crowning (CAC), the determination is made as to whether the crown fire is spreading in a passive or active mode based on the canopy bulk density (CBD) as per Van Wagner (1977):

(1) $$\mathrm{CAC} = \frac{\mathrm{CFROS_A}}{3/\mathrm{CBD}}$$

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 if 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.

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

Variable	Units	Period of change
Fuel complex		
Dead fuel moisture content	% oven-dry weight	Very short
Foliar moisture content	% oven-dry weight	Medium
Available surface fuel load [a]	kg/m^2	Long
Surface fuel layer depth	m	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	Long
Fire weather		
Wind velocity	km/h	Very short
Air temperature	°C	Very short

[a] Within the present analysis available, surface fuel load corresponds to the fuels consumed in flaming combustion, namely needle litter and small twigs < 6 mm in diameter.

Case study simulation

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

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 the thinning treatment on potential fire behaviour. The fuel complex characteristics for the unthinned and thinned (50% reduction in basal area) stands were, respectively, as follows: 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 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 percent cover > 50%) and thinned (canopy percent 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. Surface fire rate of spread was based on the fuel-type specific models developed by Cruz and Fernandes (in review).

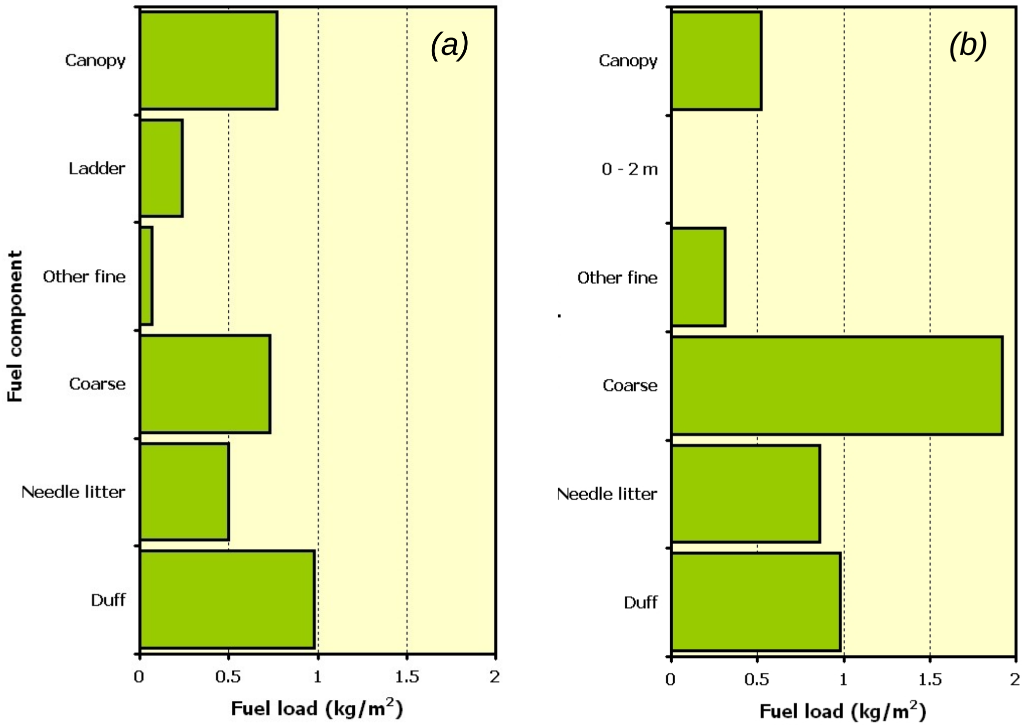

Figure 2. Fuel load distribution per fuel complex component (a) before and (b) after treatment (thinning with 50% reduction in basal area) of a 12-year old radiata pine plantation (after Williams 1978).

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. However as Williams 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, namely a reduction in crown fuel quantity, increase in fuel strata gap, an increase in surface fuel load, and changes in the stand microclimate would affect the overall fire spread and intensity potential.

The results of the simulation presented in Figure 3 show that although the changes introduced by the treatment do alter potential fire behaviour, no definitive reduction/increase trend in 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 the higher potential rate of spread within the range 20 to 30 km/h. The model system was able to identify the effect that the changes in different fuel complex properties had on the overall rate of fire spread and in identifying the thresholds for crowning activity. Importantly, the system quantified the sudden jumps 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 the lower wind speed condition (i.e., $U_{10} < 20$ km/h) 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 and within the 20-30 km/h interval, this fuel complex had the higher potential spread rate. Once $U_{10} > 30$ km/h, 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.

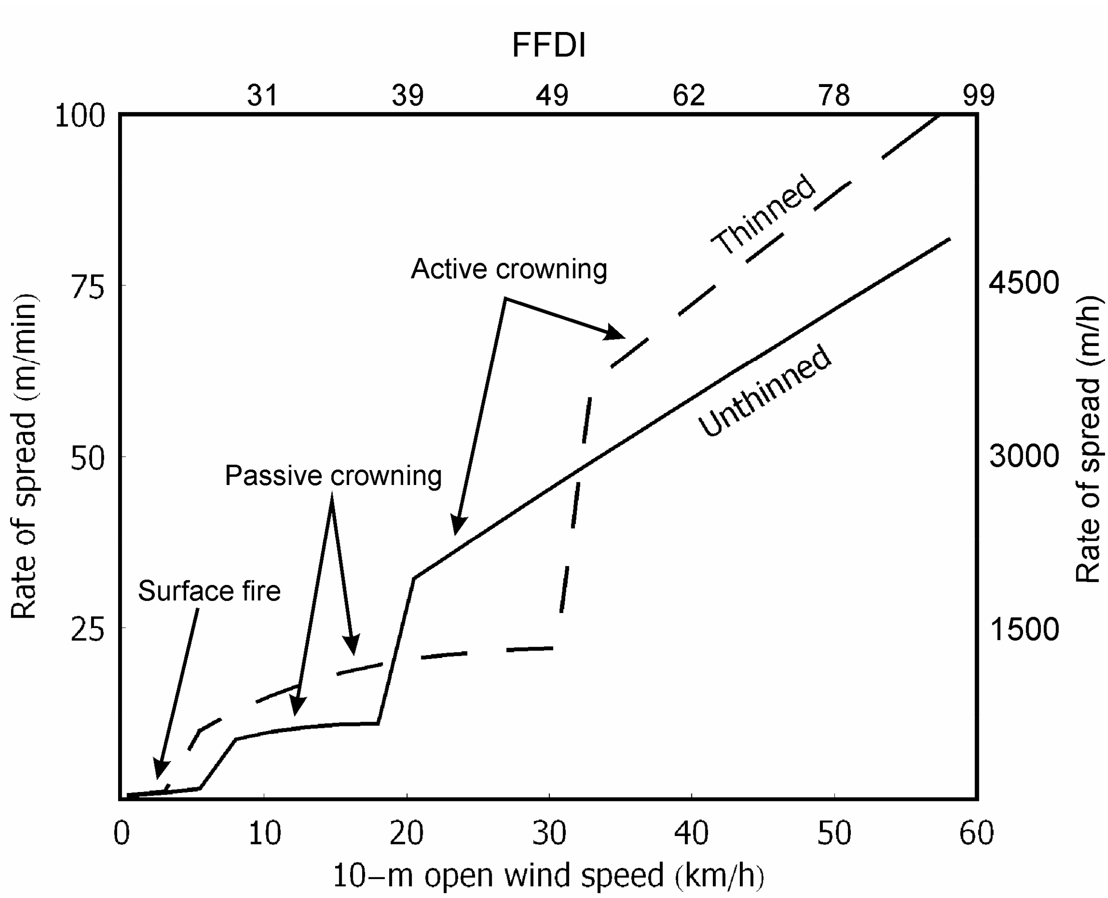

Figure 3. Head fire spread rate as a function of open wind speed for 12-year-old unthinned and thinned (50% reduction in basal area treatment) radiata pine plantation stands as per Williams (1978) (after Cruz et al 2006c). The McArthur (1967) Forest Fire Danger Index (FFDI) calculations are based on an air temperature of 40°C, relative humidity of 20%, and a Drought Factor of 10 (Noble et al. 1980).

The sudden jumps in fire rate of spread as illustrated in Figure 3 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), 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 to a crown fire. Within a pine plantation, a surface fire rate of spread is a function of the litter layer characteristics, such as fuel load, compactness and moisture content, and within stand wind speed. After crowning the flame front is subject to stronger winds (3 to 5 times higher), there is a considerably increased on the amount of fuel consumed in flaming combustion, and the fire is spreading on a fuel strata characterized 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. Evidence of abrupt changes in rate of spread after crowning on 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 (*Pinus pinaster* Ait.) plantation in Western Australia, Burrows et al. (1988) noted that when crowning did occur, the fire spread rates were 2-5 times that of the surface fires. Similarly, during an experimental burning study in maritime pine in Portugal, Fernandes et al. (2004) was able to document a near two-fold increase in rate of spread between a plot experiencing a high-intensity surface fire with individual tree torching compared to 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. The increases in rate of spread and intensity that characterize 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 3 indicates that the silvicultural treatment performed by Williams (1978) did not attain its intended purpose of reducing the fire hazard. It is worth pointing out that the thinning operation did not alter the vertical fuel continuity sufficiently and that the lack of any removal 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., high pruning and/or surface fuel reduction or removal) would be necessary to achieve a definitive reduction in fire potential. This agrees with general fuel management recommendations and is consistent with similar observations of wildfire behaviour in thinned (but without slash disposal) and unthinned pine plantations (Billings 1980; Keeves and Douglas 1983).

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 in review). The evaluation 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 high fine dead fuel moisture contents (i.e., >25%).

We have also not compared the predictions of the PPPY system with other model systems designed to predict fire behaviour in pine plantations, such as the C-6 conifer plantation fuel type model of the Canadian FBP System or the pine plantation models found in the Western Australian FFBT guide. The thoroughness to which the PPPY 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), that the PPPY system may not be applicable. In such cases, guides specifically designed for prescribed burning are superior (e.g., Byrne 1980).

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References:

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

Albini, F.A. (1983) Wind flow into a model forest re-examined. In *Preprint Volume, Seventh Conference on Fire and Forest Meteorology, 25-28 April 1983, Fort Collins, Colorado*, American Meteorological Society, Boston, Massachusetts, pp. 115-122.

Alexander, M.E. (1998) Crown fire thresholds in exotic pine plantations of Australasia. Ph.D. thesis, Australian National University, Canberra, 228 pp.

Alexander, M.E. and Cruz, M.G. (2006) Evaluating a model for predicting active crown fire rate of spread using wildfire observations. *Canadian Journal of Forest Research* **36**, 3015-3028.

Beck, J.A. (1995) Equations for the Forest Fire Behaviour Tables for Western Australia. *CALMScience* **1**, 325-348.

Billings, P. (1980) *Some aspects of the behaviour of the Caroline Fire of February 1979*. Fire Research Branch Report No. 7. Forests Commission of Victoria, Melbourne, 11 pp.

Burrows, N.D., Ward, B. and Robinson, A. (1988) Aspects of fire behaviour and fire suppression in a *Pinus pinaster* plantation. Landnote 2/88. Western Australia Department of Conservation and Land Management, Perth, 4 pp.

Burrows, N.D., Ward, B. and Robinson, A. (2000) Behaviour and some impacts of a large wildfire in the Gnangara maritime pine (*Pinus pinaster*) plantation, Western Australia. *CALMScience* **3**, 251-260.

Byram, G.M. (1959) Combustion of forest fuels. In; Davis, K.P. (ed). *Forest Fire: Control and Use*. McGraw-Hill, New York. pp. 61-89, 554-555.

Byrne, P.J. (1980) *Prescribed burning in Queensland exotic pine plantations*. Paper prepared for the Eleventh Commonwealth Forestry Conference. Queensland Department of Forestry, Brisbane, 58 pp.

Cheney, N.P. and Gould, J.S. (1997)Letter to the editor: fire growth and acceleration. *International Journal of Wildland Fire* **7**, 1-5.

Cionco, R.M. (1965) A mathematical model for air flow in a vegetative canopy. *Journal of Applied Meteorology* **4**, 517-522.

Countryman, C.M. (1972) *The fire environment concept*. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California, 12 pp.

Cruz, M.G., Alexander, M.E. and Wakimoto, R.H. (2004) Modeling the likelihood of crown fire occurrence in conifer forest stands. *Forest Science* **50**, 640-658.

Cruz, M.G., Alexander, M.E. and Wakimoto, R.H. (2005) Development and testing of models for predicting crown fire rate of spread in conifer forest stands. *Canadian Journal of Forest Research* **35**, 1626-1639.

Cruz, M.G., Butler, B.W., Alexander, M.E., Forthofer, J.M. and Wakimoto, R.H. (2006a) Predicting the ignition of crown fuels above a spreading surface fire. I: Model idealization. *International Journal of Wildland Fire* **15**, 47-60.

Cruz, M.G., Butler, B.W. and Alexander, M.E. (2006b) Predicting the ignition of crown fuels above a spreading surface fire. Part II: Model behavior and evaluation. *International Journal of Wildland Fire* **15**, 61-72.

Cruz, M.G., Butler, B.W., Alexander, M.E. and Viegas, D.X. (2006c) Development and evaluation of a semi-physical crown fire initiation model. In: Viegas, D.X. (ed). *Proceedings of 5th International Conference on Forest Fire Research, 27-30 November 2006, Figueira da Foz, Portugal*, Elsevier B.V., Amsterdam, The Netherlands, CD-ROM, 17 pp.

Cruz, M.G. and Fernandes, P.A.M. Development of fuel models for fire behaviour prediciton in maritime pine (*Pinus pinaster* Ait.) stands. In review.

Douglas, D.R. (1964) Some characteristics of major fires in coniferous plantations. *Australian. Forestry* **28**, 119-124.

Fernandes, P.A.M., Loureiro, C. and Botelho, H.S. (2004) Fire behaviour and severity in a maritime pine stand under differing fuel conditions. *Annales des Sciences Forestieres* **61**, 537-544.

Fogarty, L.G., Jackson, A.F. and Lindsay, W.T. (1996) *Fire behaviour, suppression and lessons from the Berwick Forest Fire of 26 February 1995*. Forest Research Bulletin No. 197, Forest and Rural Fire Scientific and Technical Series, Report No. 3. New Zealand Forest Research Institute, Rotorua, in association with the National Rural Fire Authority, Wellington, 38 pp. + Appendices.

Forestry Canada Fire Danger Group. (1992) *Development and structure of the Canadian Forest Fire Behavior Prediction System*. Information Report ST-X-3. Forestry Canada, Science and Sustainable Development Directorate, Ottawa, Ontario, 63 pp.

Hough, W.A. and Albini, F.A. (1978) *Predicting fire behavior in palmetto-gallberry fuel complexes*. Research Paper SE-174. USDA Forest Service, Southeastern Forest Experiment Station, 49 pp.

Keeves, A. and Douglas, D.R. (1983) Forest fires in South Australia on 16 February 1983 and consequent future forest management aims. *Australian Forestry* **46**, 148-162.

McArthur, A.G. (1965) *Fire behaviour characteristics of the Longford Fire*. Forestry and Timber Bureau Leaflet No. 91. Commonwealth of Australia, Department of National Development, Canberra, 19 pp.

McArthur, A.G. (1967) *Fire behaviour in eucalyptus forests*. Forestry and Timber Bureau Leaflet No. 107. Commonwealth of Australia, Department of National Development, Canberra, 36 pp.

McArthur, A.G., Douglas, D.R.and Mitchell, L.R. (1966) *The Wandilo Fire, 5 April 1958 – fire behaviour and associated meteorological and fuel conditions*. Forestry and Timber Bureau Leaflet No. 98. Commonwealth of Australia, Department of National Development, Canberra, 30 pp. + Appendices.

Mercer, G.N. and Weber, R.O. (1994) Plumes above line fires in a cross wind. *International Journal of Wildland Fire* **4**, 201-207.

Nelson, R.M., Jr. (2003a) Power of the fire – a thermodynamic analysis. *International Journal of Wildland Fire* **12**, 51-63.

Nelson, R.M., Jr. (2003b) Reaction times and burning rates for wind tunnel headfires. *International Journal of Wildland Fire* **12**,195-211.

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

Pearce, H.G. and Alexander, M.E. (1994) Fire danger ratings associated with New Zealand's major pine plantation wildfires. In: *Proceedings of 12th Conference on Fire and Forest Meteorology, 26-28 October 1993, Jekyll Island, Georgia*, SAF Publication 94-02. Society of American Foresters, Bethesda, Maryland, pp. 534-543.

Pearce, H.G. and Anderson, S.A.J. (compilers). (2007) *A manual for predicting fire behaviour in New Zealand fuel types*. Ensis Bushfire Research Group, Christchurch, New Zealand.

Rothermel, R.C. (1972) *A mathematical model for predicting fire spread in wildland fuels*. Research Paper INT-115. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah, 40 pp.

Rothermel, R.C. (1983) *How to predict the spread and intensity of forest and range fires*. General Technical Report INT-143. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah, 161 pp.

Sneeuwjagt, R.J., and Peet, G.B. (1985) *Forest fire behaviour tables for Western Australia*. Third edition. Western Australia Department of Conservation and Land Management, Perth, 59 pp.

Van Wagner, C.E. (1977) Conditions for the start and spread of crown fire. *Canadian Journal of Forest Re*search **7**, 23-34.

Williams, D.F. (1978) *Fuel properties before and after thinning in young radiata pine plantations*. Fire Research Branch Report No 3, Forests Commission of Victoria, Melbourne, 17 pp.

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