CSIRO PUBLISHING

International Journal of Wildland Fire **2008**, *17*, 194–204 www.publish.csiro.au/journals/ijwf

Development of fuel models for fire behaviour prediction in maritime pine (*Pinus pinaster* Ait.) stands

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Abstract. A dataset of 42 experimental fires in maritime pine (*Pinus pinaster* Ait.) stands was used to develop fuel models to describe pine litter and understorey surface fuel complexes. A backtracking calibration procedure quantified the surface fuel bed characteristics that best explained the observed rate of fire spread. The study suggested the need for two distinct fuel models to adequately characterise the variability in fire behaviour in this fuel type. In these heterogeneous fuel beds the fuel models do not necessarily represent the inventoried average fuel conditions.

Evaluation against the modelling data produced mean absolute errors of 0.8 and 0.6 m min^{-1} in rate of spread, respectively, for the litter and understorey fuel models, with little evidence of bias. The fuel models predicted the rate of spread of a validation dataset with comparable error. Comparison of the behaviour and evaluation statistics produced by the study fuel models with fuel models developed from inventoried fuel data alone revealed an improvement on model performance for the current study approach for the litter fuel model and comparable behaviour for the understorey one.

We examined model behaviour through comparative analysis with models used operationally to predict fire spread in pine stands. Large departures from model behaviour essentially occur when the models are exercised outside the range of the model development dataset. The discrepancies in predicted fire behaviour were hypothesised to arise not from differences in fuel complex structure but from the selected functional relationships that determine the effect of wind and fuel moisture on rate of spread.

Additional keywords: pine plantation, Rothermel model, surface fire, surface fire spread.

Introduction

Pine plantations are an important worldwide forest resource that delivers a range of societal, economical and environmental benefits. The combination of rapid growth, high stocking, surface fuel accumulation and shade tolerance of some tree species, e.g. *Pinus radiata*, create extremely flammable fuel structures in the absence of proactive silvicultural and fuel management (McArthur *et al.* 1966; Geddes and Pfeiffer 1981). Fire behaviour models allow assessment of the fire potential associated with a certain fuel complex under pre-defined burning conditions, e.g. worst-case scenario, and fire management strategies can be devised accordingly. These models are necessary to explore and evaluate the effects of treatments to mitigate a fire hazard, either at stand or landscape level. Other applications of fire behaviour models are to support prescribed fire planning and tactical decision making for wildfire suppression.

The fire sensitivity and economic value associated with pine stands have restricted some of the experimental work required to develop and evaluate fire behaviour models. Consequently only a few fire behaviour prediction systems have the ability to predict fire characteristics in pine stands, namely, the C-6 (conifer plantation) fuel type of the Canadian Forest Fire Behaviour Prediction System (Forestry Canada Fire Danger Group 1992), the radiata and maritime pine adaptations of the Western Australia Forest Fire Behaviour Tables (Sneeuwjagt and Peet 1985) and systems based on the Rothermel (1972) surface fire spread model, e.g. BehavePlus (Andrews *et al.* 2003) and Farsite (Finney 2004). The Rothermel model requires the description of the physical characteristics of the surface fuel bed through the fuel model concept. A user can choose between a set of standard fuel models (Anderson 1982; Scott and Burgan 2005) or develop a custom one based on measured or estimated fuel data (Burgan and Rothermel 1984). This capability to integrate the description of site specific fuels should in part explain why systems based on the Rothermel (1972) model have gained popularity outside the USA (e.g. Van Wilgen *et al.* 1985; Weicheng 1996; Lopes *et al.* 2002).

Fuel models are likely to be unsuccessful when developed without calibrating the predictions or tuning the parameters against fire behaviour observations, especially in horizontally oriented fuel beds, e.g. fuel complexes with litter-dominated surface fuel layers. Studies aimed at evaluating the Rothermel (1972) fire spread model with custom based fuel models in litter fuels have revealed high under prediction bias (e.g. Lawson 1972; McAlpine and Xanthopoulos 1989; Cruz and Viegas 1998;

10.1071/WF07009 1049-8001/08/020194

Burrows 1999; Hély *et al.* 2001). This bias arises from (1) the fire spread model oversensitivity to fuel bed compactness (Catchpole *et al.* 1993), and (2) the difficulty in defining what proportion of the fine fuels is driving the fire spread in heterogeneous fuel layers. The Rothermel (1972) surface fire spread model was developed under near-homogeneous fuel conditions. Its application to naturally occurring heterogeneous fuels, namely a surface fuel bed in which fuel compactness increases with depth, might require adjustment. As described by Albini (1982) and Cheney (1990), fire spreads in litter fuels with an ignition interface that travels horizontally on the surface of the fuel bed (where fuels are less compact and usually drier) and downward into the fuel bed. The downward spread occurs behind the leading edge of the fire, and the energy release contributes to the flame dimensions and the turbulent environment that interacts with the wind, which causes unsteady flame flickering and flame contact with unburned fuels. Nonetheless, and although fire spread is dependent on the energy released by the lower layers of the fuel bed, it is its upper layer, which will be only a fraction of the total fuel bed, that largely determines the fire rate of spread. In a fuel model developed from inventoried fuel data, the averaged fuel bed compactness and packing ratio are higher than what characterises the top layer of the surface fuel bed. This will bias the rate of spread model to low reaction rates, and correspondingly to lower than expected rates of fire spread.

The development of fuel models that describe the surface fuel layer of pine stand fuel complexes would allow the users of fire behaviour prediction systems to better understand fire dynamics in these fuel types. The existence of such fuel models would enable the integration of the Rothermel (1972) model with crown fire initiation and spread models (e.g. Cruz *et al.* 2005, 2006) to predict the full range of fire behaviour in pine plantations over a variety of fuel complex structures and fire environments. Such a model system is an essential tool to merge silviculture with fire management (Johnson and Peterson 2005) to allow understanding of the flammability associated with a given silvicultural system and the analysis of 'what-if' scenarios related to the implications of silvicultural operations and fuel treatments on fire behaviour potential.

Maritime pine (*Pinus pinaster* Ait.) is a widespread species in the western Mediterranean Basin and is among the most fire prone vegetation types in the region (Tapias *et al.* 2004; Nunes *et al.* 2005). Plantations of the species are notably flammable (McArthur *et al.* 1966; Burrows *et al.* 1988, 2000; Fernandes *et al.* 2004), partly because its litter fuel characteristics are highly favourable to ignition and combustion (Dupuy 1995). Such a fire hazard potential is exacerbated in young stands, whether they are dense or open, due to vertical fuel continuity. The objectives of this paper were (1) to develop fuel models for maritime pine stands through a calibration procedure based on backtracking, and (2) evaluate the performance of the Rothermel (1972) surface fire spread model within this fuel type against independent data and through comparative analysis with other models.

Methods

Data

The available data originated from an experimental burning program conducted in maritime pine stands in northern Portugal (Fernandes *et al.* 2002), and from a stand alone high intensity experiment (Fernandes *et al.* 2004). The stands were established by plantation or by regeneration after wildfire, with ages that ranged from 14 to 41 years, a basal area from 14 to 56 $m^2\ ha^{-1}$ and dominant height from 7.8 to 18.7 m. The understorey vegetation is representative of western Iberia maritime pine stands in the transition from Atlantic to Mediterranean climate influences and is composed mainly of *Erica umbellatta*, *Pterospartium tridentatum* and *Ulex minor* shrubs, and by bracken fern (*Pteridium aquilinum*).

Data obtained under poor burning conditions (dead fuel moisture content in excess of 29% and windspeed (within stand measured at 2 m) lower than 1 $km\ h^{-1}$), which leads to broken fire fronts, were excluded. Exploratory analysis of the dataset revealed large uncertainty for fires carried out on slopes steeper than 15°. This was suspected to be due to difficulties in measuring rate of spread in these particular fires and the non-attainment of pseudo steady-state fire propagation. We decided to exclude these fires from the analysis. The resulting dataset was divided into two subsets based on the surface fuel strata characteristics. The subsets correspond, respectively, to stands with a litter-dominated surface fuel bed and stands with a significant understorey component, in which fire propagation is determined by the shrub–litter array.

Pre-burn fuel assessment was based on double sampling techniques by conducting destructive sampling outside the experimental plots and measuring cover and depth along line transects located both outside and inside the plots. Within the sample quadrats all fine (diameter < 6 mm) fuel was collected and divided by layer of origin, respectively, shrubs, surface litter (forest floor, L layer) and upper duff (forest floor, F layer). Fuel load was estimated for the individual plots by combining the quadrat mean bulk density of each layer with its transect assessment of volume (Fernandes 2002; Fernandes *et al.* 2004).

A large proportion of the fire experiments were conducted under mild weather conditions, typical of the low to moderate fire danger that conforms to the practice of prescribed burning and prevails from mid-Autumn to early spring. A few burns, however, were accomplished under drier conditions, in mid-summer (Fernandes *et al.* 2004) and mid to late spring. As a consequence, the observed fire behaviour covered the surface fire spectrum well, from fires near the limit of sustained flaming combustion to high-intensity fires that induce partial or total tree torching.

Modelling approach

We aimed to evaluate the adequacy of the Rothermel (1972) surface fire spread model to predict the rate of spread in pine stands. Fuel model fitting relied on a backtracking method (Hough and Albini 1978; Systems for Environment Management 1986). This method systematically calculates several possible solutions from a set of input combinations. In our particular case, it creates and tests a large number of alternative fuel models, as a result of the possible combinations of fuel parameters. We varied fuel model parameters within the range of variability found on fuel inventory (Table 1) to determine the fuel model that best predicted fire spread in the dataset. The criterion for the best prediction was the smallest root mean square error. This method differs from the approach of Burgan and Rothermel (1984) in which fuel models are developed from average sampled fuel bed characteristics.

Table 1. Descriptive statistics for environmental, fuel and fire behaviour variables associated with the litter and understorey fuel types

Variable	Litter fuel bed ($n = 12$)		Understorey fuel bed ($n = 30$)	
	Mean (s.d.)	Min.–max.	Mean (s.d.)	Min.–max.
Environmental variables				
Temperature (°C)	11.3 (7.1)	4.8–29.6	13.9 (5.0)	1.8–29.1
Relative humidity (%)	53.9 (17.3)	24.2–94.3	43.1 (13.6)	25.7–70.5
2-m windspeed (km h^{-1})	4.7 (3.13)	0.5–9.8	3.1 (1.9)	1–9.1
Slope (deg)	4.3 (5.4)	0–11.3	2.85 (3.3)	0–8.5
Fuel variables				
Litter L-layer depth (m)	0.027 (0.009)	0.016–0.045	0.027 (0.01)	0.014–0.066
Litter F-layer depth (m)	0.028 (0.013)	0.007–0.053	0.030 (0.011)	0.017–0.063
Litter total depth (m)	0.056 (0.015)	0.032–0.083	0.056 (0.013)	0.037–0.092
Shrub height (m)	–	–	0.54 (0.25)	0.3–0.75
Litter L-layer load (kg m^{-2})	0.51 (0.16)	0.28–0.82	0.48 (0.18)	0.26–1.19
Litter F-layer load (kg m^{-2})	1.13 (0.64)	0.32–2.45	1.34 (0.44)	0.79–2.58
Litter total load (kg m^{-2})	1.63 (0.66)	0.77–2.85	1.83 (0.42)	1.14–2.85
Shrub load (kg m^{-2})	–	–	0.69 (0.22)	0.31–1.1
Shrub cover (%)	–	–	71 (19.9)	30–100
Dead fuel moisture (%)	19.6 (7.4)	3.7–29.3	17.0 (6.8)	4.2–29.6
Live fuel moisture (%)	–	–	98.7 (17.2)	83.2–157.6
Fire behaviour variables				
Rate of spread (m min^{-1})	1.7 (1.1)	0.25–3.6	2.0 (1.42)	0.36–6
Fire intensity (kW m^{-1})	318 (265)	47–881	1130 (847)	203–3411

For the litter fuel bed the ranges (increment in parenthesis) in properties used in the simulation were: 1-h fuel load, 0.5–0.8 (0.05) kg m^{-2}; 10-h fuel load, 0.15–0.3 (0.05) kg m^{-2}; fuel bed depth, 0.025–0.1 (0.025) m; dead fuel surface area-to-volume ratio, 4500–6000 (500) m^{-1}; and moisture of extinction, 30–45 (2.5)%. The range in fuel bed height was higher than the range given in Table 1. This is justified by the oversensitivity of the Rothermel (1972) model to fuel bed compactness, as discussed previously. For the understorey and litter fuel bed the ranges in fuel bed properties used in the simulation were: 1-h fuel load, 0.25–1.2 (0.05) kg m^{-2}; 10-h fuel load, 0.15–0.4 (0.05) kg m^{-2}; live woody fuel load, 0.3–1.1 (0.1) kg m^{-2}; fuel bed depth, 0.2–0.7 (0.05) m; dead fuel surface area-to-volume ratio, 4500–6000 (500) m^{-1}; live fuel surface area-to-volume ratio, 4500–6000 (500) m^{-1}; and moisture of extinction, 30–45 (2.5)%. This resulted in 2688 and 1 140 480 possible fuel combinations, respectively, for the litter and the understorey fuel models.

Model evaluation

We evaluated the fuel models through: (1) error statistics, (2) analysis of behaviour, (3) prediction capacity against independent data and (4) comparison with empirically based models. The statistics used in the evaluation were difference measures (Willmott 1982): the root mean square error (RMSE), the mean absolute (MAE) and percent (MA%E) errors and mean bias error (MBE):

$$\mathrm{RMSE} = \sqrt{\frac{\sum (y_i - \hat{y}_i)^2}{n}} \tag{1}$$

$$\mathrm{MAE} = \frac{\sum |y_i - \hat{y}_i|}{n} \tag{2}$$

$$\mathrm{MA\%E} = \frac{\sum \left(\frac{y_i - \hat{y}_i}{y_i}\right)}{n} \times 100 \tag{3}$$

$$\mathrm{MBE} = \frac{\sum (\hat{y}_i - y_i)}{n} \tag{4}$$

where y_i and $\hat{y}_i$ are, respectively, the observed and predicted rate of fire spread. Model predictions were compared with independent data compiled from experimental and prescribed fires conducted in stands of several different pine species, namely: red pine, *Pinus resinosa* (Van Wagner 1968; $n = 6$), radiata pine, *Pinus radiata* (McArthur and Cheney 1966; Burrows *et al.* 1989; $n = 3$) and lodgepole pine, *Pinus contorta* (Lawson 1972; $n = 8$). All the fires were surface fires that exhibited moderate intensity, with a rate of spread in the dataset that ranged from 0.9 to 6.1 m min^{-1}.

We compared the behaviour of the Rothermel (1972) model that incorporated the pine fuel models with three fire behaviour models to describe fire rate of spread in pine stands. Two of the models are currently used by fire management agencies and the third is an empirically based model (Fernandes *et al.* 2002), which was developed with the dataset used to calibrate the fuel models. The operational models were (1) the Western Australia Forest Fire Behaviour Tables (FFBT) adjustment for maritime pine stands (Sneeuwjagt and Peet 1985; Beck 1995) and (2) the surface fire spread equation of the conifer plantation (C-6) fuel type of the Canadian Forest Fire Behaviour Prediction (CFFBPS) System (Forestry Canada Fire Danger Group 1992). The FFBT estimates for maritime pine assumed a fuel load of 0.5 and 1.2 kg m^{-2}, respectively, for comparison with the litter and understorey fuel models (based on Table 1 fine dead and live fuel load). The conifer plantation C-6 fuel type requires input

Table 2. Fuel model parameters determined for litter and understorey dominated fuel beds in maritime pine stands

δ, fuel depth; σ, surface area-to-volume ratio; M_x, dead fuel moisture of extinction

Fuel model	Fuel load (kg m^{-2})					δ (m)	σ (m^{-1})		M_x (%)
	1 h	10 h	100 h	Live herb	Live shrub		Dead 1 h	Live fine	
Litter	0.65	0.15	–	–	–	0.1	5500	–	45
Understorey	0.8	0.3	–	–	0.35	0.35	5500	6000	45

indices of the Canadian Fire Weather Index System, namely the Fine Fuel Moisture Code (FFMC) and the Initial Spread Index (ISI). Conversion from fine dead fuel moisture content to FFMC relied on the function implemented in the CFFBPS system (Van Wagner 1987). ISI was estimated from FFMC and 10-m open windspeed. Conversion from within stand windspeed – herein assumed equal to eye level and mid-flame windspeed, used as input in the remaining models – to 10-m open windspeed assumed a 3 : 1 ratio as suggested by Van Wagner (see McAlpine and Xanthopoulos 1989)[A]. Both the CFFBPS C-6 and the FFBT systems consider crown fire propagation. To restrict the CFFBPS C-6 predictions to the surface phase, the canopy base height was set to 20 m. The FFBT system does not allow for a similar constraint and it is expected that the spread rate simulations for low fuel moistures and high winds will correspond to crown fires.

The model comparison was based on the deviation in predicted rate of spread for a given random combination of wind and fine dead fuel moisture content. Within stand windspeeds varied in the 0–15 km h^{-1} range and fine dead fuel moisture content between 4 and 25%. Slope is another environmental variable that is common to all models and whose effect is treated differently between them. Analysis of the distinct slope functions have been carried out by Van Wagner (1977).

We also examined the sensitivity of the various models to changes in windspeed and fine dead fuel moisture content. The index of sensitivity, which indicates the proportional response of the model to changes in the perturbed input parameter, was defined as (Bartelink 1998; Cruz *et al.* 2003):

$$\mathrm{RS} = \frac{\frac{\partial y}{\partial x} \times \Delta_x}{y_{\mathrm{def}} \times \Delta_{\mathrm{IV}}} \tag{5}$$

where y is the resulting value of the output parameter when the value of the input parameter, x, is changed by ±10% (Δ_x), y_{def} is the output parameter under default conditions and Δ_{IV} is the range of the perturbation (fixed at 0.2). The sensitivity tests were based on 100 runs with randomly selected input conditions within the range specified for the model comparison.

Table 3. Model performance statistics for the maritime pine litter and understorey fuel models

Fuel model	RMSE	MAE (m min^{-1})	MA%E (%)	Percentage within ±25% error	MBE (m min^{-1})
Litter	1.14	0.82	37	50	−0.40
Understorey	0.77	0.6	45	50	0.02

Results

Model fit

The backtracking procedure produced distinct fuel models for the litter and understorey surface fuel beds (Table 2). The differences between the fuel models emphasise the differences in the fire behaviour associated with each fuel bed. The understorey fuel model had slightly higher dead fuel loads, and a live fuel component that corresponded to the shrub understorey and a deeper fuel bed. For both fuel models the fuel particle surface area-to-volume ratio (σ) and moisture of extinction (M_x) were within experimental measurements (Fernandes and Rego 1998; Fernandes *et al.* 2002). The fuel particle surface area-to-volume ratio weighted to the fuel bed array was 5400 and 5600 m^{-1} for the litter and understorey fuel models. The litter fuel model had a fine fuel load (0.65 kg m^{-2}) higher than the average of the dataset (0.51 kg m^{-2}) and a fuel bed height of 0.1 m, which is higher than the upper limit of the dataset range (0.045 m). The understorey fuel model fine dead and live shrub fuel loads were lower than the dataset average values. For this fuel model, fuel bed height, which encompassed the litter and shrub layers, was lower than the measured average. The calculated fuel bed packing ratios were 0.015 and 0.0081 for the litter and understorey fuel models, respectively. The ratio between the observed and optimum packing ratio, the packing ratio that maximises the potential reaction velocity and reaction intensity (Rothermel 1972), was 2.01 for the litter and 1.07 for the understorey fuel model.

Table 3 presents model fit statistics for the developed fuel models. The understorey fuel model produced a better fit to the data, with an RMSE of 0.77, MA%E of 45% and an MBE of −0.02 m min^{-1}, whereas the litter fuel model produced an

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[A] The correspondence between the within stand and the 10-m open windspeed can induce some artificial discrepancies in the model comparison. The C-6 fuel type model was fitted using an observed 3 : 1 wind ratio (McAlpine and Xanthopoulos 1989). In Western Australia, a ratio of 5 : 1 is suggested for well stocked pine plantations (Sneeuwjagt and Peet 1985).

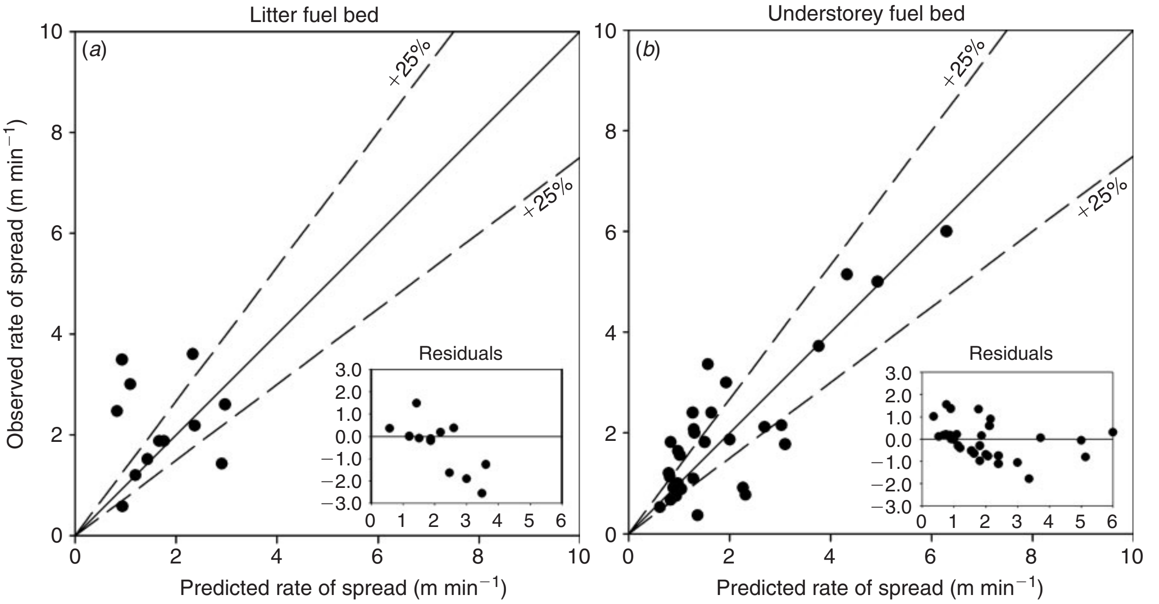

Fig. 1. Predicted *v.* observed spread rates of surface fires for litter and understorey fuel models. *x*-axis on the residual plot is the observed rate of spread.

Table 4. Model evaluation statistics with independent experimental/prescribed fire data

Fuel types	RMSE	MAE (m min^{-1})	MA%E (%)	Percentage within ±25% error	MBE (m min^{-1})
Red pine ($n = 6$)	1.63	1.05	42	17	−1.04
Radiata pine ($n = 3$)	1.06	1	45	0	−0.99
Lodgepole pine ($n = 8$)	0.53	0.44	41	63	0.33
All fires ($n = 17$)	1.13	0.75	42	35	−0.39

RMSE of 1.14, MA%E of 35% and an MBE of −0.40 m min^{-1}. The predicted *v.* observed scatter plot of Fig. 1*a* reveals a larger data point dispersion for the litter fuel model, which probably resulted from differences in fuel load and structure between and within fire plots. Litter depth was less variable in the understorey plots than in the litter plots (Table 1). Some of the litter plots were located in a stand where localised residues from pruning increased litter aeration and the surface fuel layer heterogeneity: downed dead woody fuels (1, 10 and 100 h) in 1-m^2 quadrats ($n = 15$) averaged 0.67 kg m^{-2} but varied almost 10-fold, from 0.20 to 1.72 kg m^{-2}.

Evaluation against independent data

Table 4 gives the statistics from the assessment of model performance against independent data. From the description of fuels in the original papers, the surface fuel beds for the red, lodgepole and radiata pine stands were assumed to be described by the litter fuel model. The Rothermel (1972) model predicted the rate of spread with an average RMSE of 1.13 and an MA%E between 41 and 45%. Overall, 35% of the predictions had an error smaller than 25%. The results indicated a negative bias, under prediction (Fig. 2), for the red (MBE = −1.04 m min^{-1}) and radiata

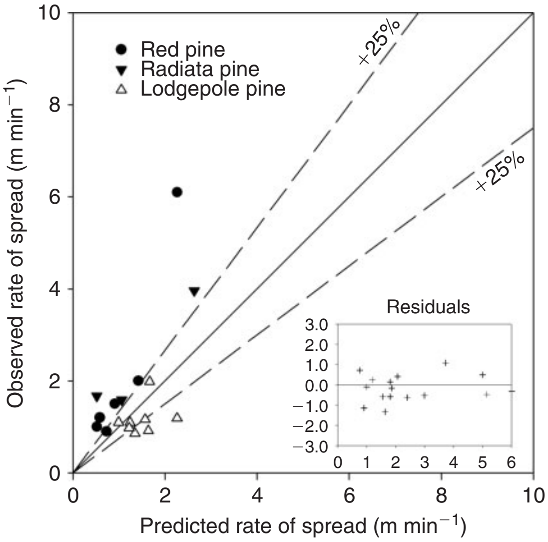

Fig. 2. Predictions from the litter fuel model *v.* observed spread rates of experimental and prescribed surface fires in pine stands. *x*-axis on the residual plot is the observed rate of spread.

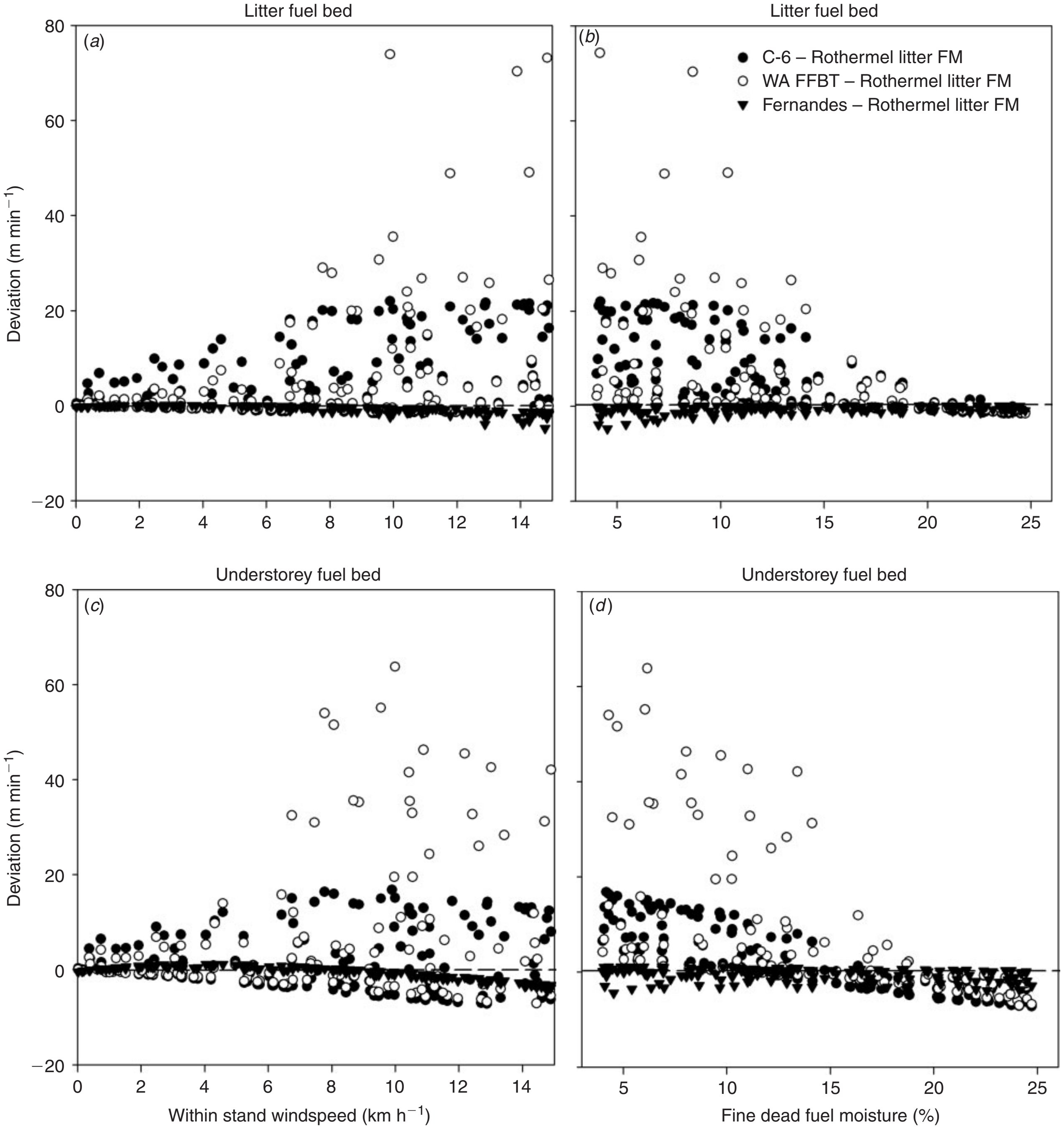

Fig. 3. Deviation between Rothermel (1972) spread model outputs and CFFBPS C-6, WA FFBT maritime pine and Fernandes *et al.* (2002) model predictions. (*a*) and (*b*) report to simulations for a surface fuel bed constituted solely by litter and (*c*) and (*d*) to simulations for a surface fuel bed constituted by understorey and litter. The FFBT simulation assumes an available fuel load of 0.5 and 1.2 kg m^{-2} for litter and understorey fuel beds, respectively. The understorey model of Fernandes *et al.* (2002) assumes an understorey height of 0.5 m. Live fuel moisture content is fixed at 100%.

pine fires (MBE = -0.99 m min^{-1}), and a slight over prediction trend for the lodgepole pine fires (MBE = 0.33 m min^{-1}).

Comparisons with other models

The deviation between the rate of spread predicted by the Rothermel (1972) model that incorporated the pine fuel models and the other three fire spread models under analysis is given in Fig. 3. The deviations in this figure are the difference between the prediction of any of the three fire spread models and the Rothermel (1972) model output. A positive deviation indicates that the Rothermel model predicts a lower spread rate for that specific windspeed–fine dead fuel moisture combination. For the litter fuel bed (Fig. 3*a*, *b*), the model that yielded the largest deviation from the Rothermel (1972) model is the Western Australia

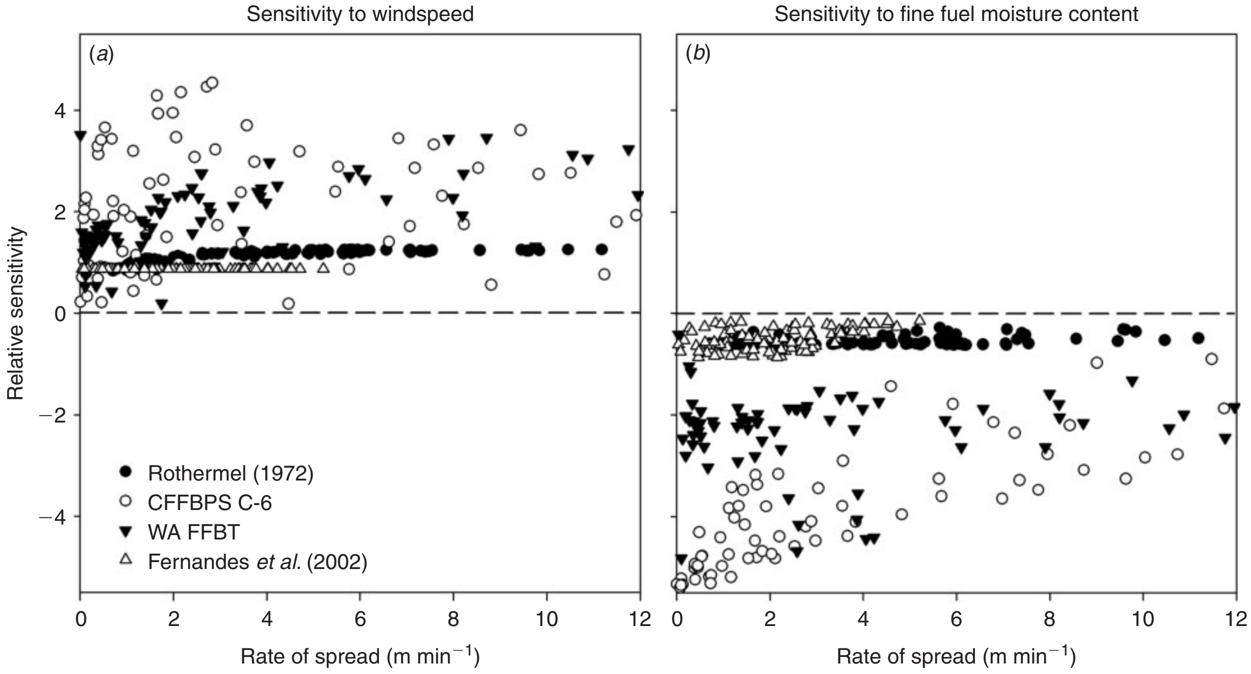

Fig. 4. Relative sensitivity to (*a*) windspeed and (*b*) fine fuel moisture content for the Rothermel (1972), CFFBPS C-6, WA FFBT maritime pine adjustment and Fernandes *et al.* (2002) fire spread models.

FFBT maritime pine model, with the differences increasing with an increasingly severe fire environment. A similar trend occurs for the CFFBPS C-6 model. For mild burning conditions, i.e. low windspeeds and high fuel moisture content, the differences in model predictions are relatively small. The model of Fernandes *et al.* (2002) predicts lower rates of spread than the Rothermel (1972) model for high windspeeds and low fuel moistures and comparable predictions for other burning conditions. Overall the results for the understorey fuel model are comparable (Fig. 3*c*, *d*), although the differences between the Rothermel (1972) and the Fernandes *et al.* (2002) model predictions are smaller.

The large differences that occur between the CFFBPS C-6 and the Western Australia FFBT maritime pine models and the Rothermel (1972) predictions for pine stands can be attributed to the functional form for the wind and fuel moisture effect on fire rate of spread in the former models. Whereas the Rothermel (1972) and the Fernandes *et al.* (2002) models rely on power functions, the CFFBPS C-6 and FFBT models rely on exponential type functions to describe the effect of wind on rate of spread. In the higher end of the windspeed spectrum this results in large increases in rate of spread for moderate changes in windspeed. The wind exponents determined for the two fuel models were 1.37 and 1.40, respectively, for the litter and understorey fuel beds. These values are within the range of non-linear fits determined in empirical studies (see Fendell and Wolff 2001).

A further source of deviation between the FFBT and the Rothermel model predictions arise from the use of a few fast spreading wildfires in the development of the FFBT system. For severe burning conditions the model supposedly predicts the spread rate of crown fires, hence the larger deviations observed.

The purpose of the sensitivity analyses was to quantify the sensitivity of the various models to input variables under a range of burning conditions. The relative sensitivity (RS) scores plotted against a range of rate of spread of surface fires (up to 12 m min^{-1}) are given in Fig. 4. The non-linear response to input variables of most of the models is noticeable. The Rothermel (1972) spread model is moderately sensitive ($1.0 < |\mathrm{RS}| < 2.0$) to windspeed and slightly sensitive ($0.5 < |\mathrm{RS}| < 1.0$) to insensitive ($0.0 < |\mathrm{RS}| < 0.5$) to variation in fine fuel moisture content. The insensitivity of the model to variation in this latter parameter comes from the polynomial form of its fuel moisture function, which induces a small fuel moisture damping effect within the middle range of fuel moisture content (see fig. 24 in Rothermel 1972). This fire spread model shows a relatively constant sensitivity to input variables throughout the tested range of rate of spread.

Both the CFFBPS C-6 and FFBT models produce a large variation of RS scores along the spectrum of simulations. The C-6 model produces the highest RS scores for the range of rate of spread considered, with a large proportion of data within the high sensitivity class ($|\mathrm{RS}| > 2.0$). Most of the FFBT model scores are found around a $|\mathrm{RS}|$ of 2. The high sensitivity and variation in sensitivity of these models to wind and fuel moisture content derives from the exponential forms of the equations that describe the effect of these variables on fire spread. The model of Fernandes *et al.* (2002) is slightly sensitive to windspeed, and slightly sensitive to insensitive to fuel moisture content.

Discussion

The semi-physical basis of the Rothermel (1972) fire spread model and the flexibility of the fuel model concept, which allows the quantitative characterisation of specific surface fuel beds, lead to a widespread application of systems based on it. A substantial research effort has been devoted to developing custom fuel models, and evaluation of the model predictions in specific fuel complexes (e.g. Hough and Albini 1978; Gould 1991; Marsden-Smedley and Catchpole 1995; McCaw 1997). The analysis of the adequacy of the Rothermel (1972) model in these studies shows a noticeable under prediction bias in horizontally oriented fuel beds, such as litter fuels (e.g. Lawson 1972; Burrows 1999; Hély *et al.* 2001; Fernandes *et al.* 2002), whereas for vertically oriented fuels, e.g. shrublands and grasslands, satisfactory results were obtained more often (Sneeuwjagt and Frandsen 1977; Rothermel and Rinehart 1983; Van Wilgen *et al.* 1985; Van Wilgen and Wills 1988; McCaw 1997). Most of the above mentioned studies used the fuel modelling method of Burgan and Rothermel (1984) to develop custom fuel models. Application of this method to litter-dominated fuel types can produce fuel models that underestimate the spread potential because of the difficulty in quantifying the fraction and packing ratio of the litter layer that is actually carrying the fire.

In the current study we apply a backtracking method to develop fuel models based on observed fire behaviour. A possible criticism of the results is that the fuel model might have fuel characteristics that are outside the range of those sampled. There are nonetheless several arguments related to how we sample fuels that sustain the validity of our approach. As discussed in the introduction, in horizontally oriented fuel beds there is a gradient in the packing ratio and the fire will be driven by the optimum one, most likely located in the upper layer of the fuel bed. Fuel beds are intrinsically heterogeneous and the fire might be controlled, not by the average or median fuel condition, but by fuel arrangements that are optimum for fire spread, i.e. fuel configurations with a higher heat transfer efficiency and/or lower heat requirements for ignition. Within a natural fuel bed the spatial distribution of these fuels constitute a path of least resistance that determines the rate of fire spread (Frandsen and Andrews 1979). What constitutes an adequate description of the fuel arrangement is unknown. Laboratory based fire spread models such as those of Rothermel (1972) or Catchpole *et al.* (2002) have been developed or calibrated under near-homogeneous fuel conditions. Extrapolation for the naturally occurring heterogeneous fuel structures assumes a homogenised fuel bed that combines all different fuel components into an equivalent single component fuel arrangement. What statistics, e.g. mean, weighted average and percentile, best describe the hypothetical fuel bed that drives the fire is unknown.

Our modelling approach, although not producing a fuel model that is an accurate representation of the average physical properties of the fuel bed, produces realistic fire spread rates. Given the above mentioned uncertainty that exists in describing the fuels that are carrying the fire, the present approach is a viable compromise to produce useful fuel models that can be linked to the Rothermel (1972) fire spread model.

Fernandes (2002) employed the same dataset used in the present study to evaluate the Rothermel (1972) model with custom fuel models based on inventoried fuel characteristics. The dead fuel moisture of extinction was held constant at 45%, but no other attempts were made to increase agreement between estimates and observations by adjusting the fuel model parameters. A reanalysis that separately considers the two fuel models is presented in Table 5. A comparison between Table 3 and Table 5 statistics shows that the improvements brought by the backtracking approach to fuel modelling were modest in the understorey fuel type (structurally vertically oriented) but noteworthy in the litter fuel complex (structurally horizontally oriented).

Table 5. Model performance statistics for the maritime pine litter and understorey fuel models of Fernandes (2002)

Fuel model	RMSE	MAE ($\mathrm{m\,min^{-1}}$)	MA%E (%)	Percentage within ±25% error	MBE ($\mathrm{m\,min^{-1}}$)
Litter	2.75	2.36	76	0	−2.36
Understorey	1.12	0.80	37	42	−0.52

The present study follows the Hough and Albini (1978) method of developing fuel models and is purportedly the method used to develop some of the original 13 standardised fuel models described in Albini (1976) and Anderson (1982). The performance measures obtained in the present study show the capability of the Rothermel (1972) model to satisfactorily predict fire spread in pine stands. Model verification against the design data used for the model calibration produced mean percentage errors of 37 and 45%, respectively, for the litter and understorey fuel models. Statistics from the model evaluation against independent datasets, namely a mean percentage error of 42% (Table 4) were within the range of uncertainty obtained in other fire behaviour studies (Tables 6 and 7).

Within the fire research and management communities, there has not been a clear statement of required accuracy for fire spread models. As stated by Andrews (1980) and Alexander and Cruz (2006), such a measure depends on the values at risk and user requirements. The statistics in Tables 4–7 can be seen as indicative of the uncertainty in predicting fire rate of spread with current models. Given adequate description of fuels and weather conditions a mean absolute percentage error in the range of 25 to 50% is the level of uncertainty that users should expect from fire spread models.

The model comparison exercise showed some interesting trends, namely in the comparison between the pine fuel models and the WA FFBT adaptation for maritime pine. Under moderate burning conditions we found an acceptable agreement between the models, while for low and high fire potential the model predictions diverged considerably. Since the data used in model development are from similar fuel complexes, we believe that the differences in predicted fire behaviour essentially arise from (1) the range of rate of spread data used in the model fit, and (2) the functional relationships selected to describe the effect of environmental variables on fire behaviour. The results from Fig. 3 highlight the modelling approach effect on model behaviour. Because the development of the FFBT maritime pine adaptation incorporated wildfire data, the model attempts to describe the full range of fire behaviour, i.e. surface and crown fire propagation, based on a single equation. The exponential fit used to describe the effects of wind and fuel moisture gives the model little behavioural flexibility and the least-squares approach biases model fitting to the high fire potential data (see McCaw 1997). This possibly explains the large deviations that occur between

Table 6. Model evaluation statistics for studies that evaluate fire behaviour models with independent data from experimental and/or prescribed fires

[1] – Marsden-Smedley and Catchpole (1995); [2] – Cruz *et al.* (2005) against ICFME data (Stocks *et al.* 2004); [3] – Cruz *et al.* (2005) for passive crown fires; [4] – Hefner data in Rothermel and Rinehart (1983); [5] – Hough and Albini (1978); [6] – Van Wilgen *et al.* (1985); [7] – Sneeuwjagt and Frandsen (1977); [8] – Bevins data in Rothermel and Rinehart (1983); [9] – Van Wilgen and Wills (1988)

Study	Range in rate of fire spread ($\mathrm{m\,min^{-1}}$)	RMSE	MAE ($\mathrm{m\,min^{-1}}$)	MA%E (%)	Percentage within ±25% error
Empirical models					
[1]	1.1–8.7	0.93	0.79	27	67
[2]	22.3–70.1	14.5	11.4	35	50
[3]	3.35–15.8	5.9	5.2	79	18
Rothermel model					
[4]	0.9–150.9	17.9	13	22	73
[5]	1.9–14.2	1.78	1.5	26	42
[6]	2.4–53.4	7.18	6.17	30	57
[7]	0.2–61.0	10.8	3.4	53	38
[8]	0.2–4.5	0.903	0.59	57	44
[9]	2.5–60.1	10.1	8.4	86	30

Table 7. Model evaluation statistics with wildfire data

[1] – Cheney *et al.* (1998); [2] – Alexander and Cruz (2006) Canadian wildfires; [3] – Alexander and Cruz (2006) US wildfires

Model	Range in rate of fire spread ($\mathrm{m\,min^{-1}}$)	RMSE	MAE ($\mathrm{m\,min^{-1}}$)	MA%E (%)	Percentage within ±25% error
[1]	66.7–383.3	60	51.4	33	33
[2]	10.7–107	19.2	14.6	49	47
[3]	13.7–80.5	18.2	15.7	61	36

the two models for low fuel moisture content and high wind conditions.

While being based on distinct datasets, the Rothermel (1972) fuel models developed herein and the CFFBPS C-6 spread model produced a combination of results worth discussing. The comparison between the CFFBPS C-6 and the Rothermel (1972) model predictions show some contradictory results. The Rothermel (1972) model predicts acceptably the data that was used to develop the C-6 surface spread equation with an MAE of $1.05\,\mathrm{m\,min^{-1}}$ and an MBE of $-1.04\,\mathrm{m\,min^{-1}}$ (red pine in Table 4). Nevertheless, when the predictions from the models are compared, noticeable differences are seen which are thought to be a function of the form of the equations used, rather than differences in the datasets. A similar issue appears when confronting the Fernandes *et al.* (2002) model with the Rothermel (1972) litter fuel model predictions. Although these were based on the same dataset, the non-linear regression analysis from the Fernandes model resulted in a minor effect of dead fuel moisture on rate of spread. The development of models based on regression analysis requires a well balanced dataset, which is difficult to obtain from outdoor experimental burning programs because of operational and safety constraints. The fuel model fitting method used in the present study, in which we combine pre-determined functional forms with fire observations, allows some of the limitations of field based datasets to be bypassed, such as correlation of explanatory variables and unbalanced distribution of data. Evidently, this advantage holds if it is assumed that the input–output relationships that underlie the Rothermel (1972) fire model are valid. Some might question this assertion, although a substantial number of studies have evaluated this model using a variety of fuel types with positive results (Table 6), which lends confidence to its validity.

Both the CFFBPS C-6 and FFBT models are used in Australasia to predict fire behaviour in pine plantations. A pertinent question that arises regards which of the models discussed in the paper is the best predictor of surface fire spread in maritime pine plantations, and possibly in other pine plantations with similar surface fuel bed structure. We believe that the Rothermel (1972) fire model with the pine fuel models is the most appropriate to predict surface fire spread under moderate to severe burning conditions. As a basis to support this assertion, the dataset used in its calibration was the most comprehensive of all models; 42 surface fires with rate of spread that ranged from 0.6 to $6.7\,\mathrm{m\,min^{-1}}$, whereas the fitting of the CFFBPS C-6 model relied on six fires (range $0.9–6.1\,\mathrm{m\,min^{-1}}$) and the FFBT maritime pine adjustment was based mostly on surface fires that burned with a low range of fire spread ($0.1–1.4\,\mathrm{m\,min^{-1}}$; unknown dataset size). Sensitivity analysis also suggests the Rothermel (1972) fire spread model to be more robust to changes in input parameters. Both the CFFBPS C-6 and FFBT models seem excessively sensitive to wind and fuel moisture content under high to extreme burning conditions, which could potentially induce large errors from small uncertainties in estimating input variables.

Conclusions

Development of fuel models to predict fire spread on maritime pine stands based on a backtracking calibrating process yielded two distinct surface fuel models, one that describes litter only fuels and the other a fuel bed constituted of an understorey shrub component and pine litter. The method used, which relies on combining field data with the Rothermel's model functional forms for the effect of environment variables on rate of fire spread, produced better results than fuel modelling approaches based on the average physical characteristics of the fuel bed.

The surface fuel models developed in this study aim at describing fire rate of spread in maritime pine stands. The adequacy of the fuel models to describe fire spread in other pine stands with structurally similar surface fuel beds, as described by fuel load, compactness and average fuel particle size requires further testing.

Acknowledgements

The authors acknowledge the review and thoughtful comments provided by Wendy Anderson, Jim Gould, Phil Cheney, Neil Burrows, Pat Andrews and two anonymous reviewers. This study was partially supported by the Portuguese Science Foundation (FCT) project 'Development of fuel models to appraise fire hazard in Portuguese wildland areas' (POCTI/AGR/61164/2004).

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Manuscript received 11 January 2007, accepted 2 October 2007