Testing a process-based fine fuel moisture model in two forest types

S. Matthews, W.L. McCaw, J.E. Neal, and R.H. Smith

Abstract: We test the ability of a recently developed process-based fine fuel moisture model to predict the surface and profile moisture content of litter fuels in two types of eucalyptus forest in Western Australia. The model predicts fuel moisture by modelling the energy and water budgets of the litter, intercepted precipitation, and the air spaces in the litter. The model equations are solved using an initial observation of fuel moisture and boundary conditions derived from basic weather observations. Model predictions are compared with twice-daily field observations made from October 1983 to March 1984. A novel two-stage method is used to assess model performance; the ability of the model to predict whether fuel is flammable is first assessed using contingency table analysis, and then the accuracy of predictions when the fuel is flammable is assessed. The model is capable of predicting the flammability of litter in both forest types with 80%–90% accuracy. Predictions of moisture content in flammable fuels are, on average, accurate to within 3% once the model has been calibrated against field observations. The model can be adapted to other forest types by specifying suitable parameters or by calibration against field observations.

Résumé : Nous avons testé la capacité d'un modèle d'humidité des combustibles fins développé récemment et basé sur les processus à prédire le contenu en humidité en surface et le long du profile des combustibles de la litière dans deux types de forêt d'eucalyptus dans l'ouest de l'Australie. Le modèle prédit l'humidité des combustibles en modélisant les bilans énergétique et hydrique de la litière, la précipitation interceptée et les espaces d'air dans la litière. Les équations du modèle sont résolues à l'aide d'une observation initiale de l'humidité des combustibles et des conditions limites dérivées d'observations météorologiques de base. Les prédictions du modèle sont comparées à des observations faites sur le terrain deux fois par jour du mois d'octobre 1983 au mois de mars 1984. Une nouvelle méthode à deux étapes est utilisée pour évaluer la performance du modèle. La capacité du modèle à prédire si les combustibles sont inflammables est d'abord évaluée à l'aide de l'analyse par tableau de contingence et par la suite la précision des prédictions est évaluée lorsque les combustibles sont inflammables. Le modèle est capable de prédire la l'inflammabilité de la litière dans les deux types de forêt avec une précision de 80 % à 90 %. Les prédictions du contenu en humidité dans les combustibles inflammables sont en moyenne précises en dedans de 3 % une fois que le modèle a été calibré à partir d'observations faites sur le terrain. Le modèle peut être adapté à d'autres types de forêt en spécifiant les paramètres appropriés ou en le calibrant à partir d'observations faites sur le terrain.

[Traduit par la Rédaction]

Introduction

The moisture content of dead fine fuels (FMC) is an important determinant of ignition probability and bushfire behaviour. Above ~25% FMC, fuels will not ignite (Catchpole 2001), and fire intensity, rate of spread, and suppression difficulty increase as fuel moisture decreases (Luke and McArthur 1978). Thus, accurate knowledge of FMC is required to predict whether fuels will burn and, if ignition is sustained, subsequent fire behaviour. Because making field measurements of FMC is labour intensive and because there is a need to predict FMC for planning prescribed burning and to predict fire behaviour for wildfire suppression operations, models are used to predict FMC from weather observations or forecasts.

Matthews (2006) developed a new fuel moisture model that predicted fuel moisture by modelling the physical processes in a forest litter layer and tested the model against short runs of observations from eucalyptus mallee-heath in southwestern Western Australia and *Eucalyptus obliqua* L'Her. forest in Tasmania. The process-based modelling approach offers potential advantages over existing empirical models in that a process-based model can be adapted for different forest types and locations by changing model parameters without the need for extensive and expensive field sampling programs. Also, incremental improvements can be made to the model as new knowledge becomes available.

However, because the model was developed from laboratory measurements and theory, several issues must be addressed before it can be used with confidence. Running the model requires detailed hourly weather information, which

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is not normally available from fire weather observations, so it must be possible to synthesize hourly weather from basic observations. The model distinguishes between different types of litter layers using 26 parameters including fuel load, equilibrium moisture content, and other physical properties of the litter (Matthews 2006). It must be possible to correctly represent different litter layers using parameters that are easily measured. The field response of the model has only been tested and shown to be successful over a narrow range of conditions so far. To be useful, the model must work under all conditions that are of interest to the fire manager. Finally, the model predictions when the fuel is flammable must be accurate if they are to be used to make fire behaviour predictions. This paper addresses these issues by testing model predictions against 5 months of twice-daily fuel moisture observations from two forest types in southwestern Western Australia.

Theory

Studies comparing model predictions and field measurements of FMC have previously been conducted using eucalyptus (Viney and Hatton 1989; Pook 1993; Gould 1994; McCaw 1998; Catchpole et al. 2001; Weise et al. 2005; Matthews 2006), pine (Loomis and Main 1980; Harrington 1982; Simard and Main 1982; Simard et al. 1984; Rothermel at al. 1986; Nelson 1991; Pook 1993; Weise et al. 2005; Wotton et al. 2005), grass (Rothermel et al. 1986; Marsden-Smedley and Catchpole 2001; Weise et al. 2005), fern (Weise et al. 2005), and heath fuels (Plucinski 2004) and pine hazard rods (Burgan 1987; Nelson 2000) in Australia and North America. These studies have aimed either to validate models in the fuel types for which the models were developed or to select from a suite of candidates the most suitable model for a novel fuel type.

The success of models has been judged by a combination of subjective expert assessment of predictions and statistical measures. Early studies used linear regression and correlation statistics to characterize model performance. In a review of such studies, Viney and Hatton (1989) noted that these statistics provide little information about bias in predictions. More recent studies have usually corrected this deficiency by reporting the model's mean error (ME), defined as $\Sigma_i(x_i - \hat{x}_i)/n$ where $\hat{x}_i$ is the model prediction of the ith of n observations, x_i. Scatter in predictions has been described by mean absolute error (MAE), defined as $\Sigma_i\left|x_i - \hat{x}_i\right|/n$ and root mean square error (RMSE), defined as $\sqrt{\Sigma_i(x_i - \hat{x}_i)^2/n}$ (Catchpole et al. 2001). Catchpole et al. (2001) note that MAE is more robust against outliers than RMSE. In some studies, the accuracy of the model has been quantified by the fraction of model predictions that fall within a given range about the observed moisture content, with tolerances of between 1% and 3% used. Hereafter, this collection of statistical measures is referred to as "validation statistics."

Many of the fuel moisture models examined in previous studies have had no capacity to predict the effect of rainfall or dew on fuel moisture. As a consequence, it has been common to exclude observed fuel moisture values above the fibre saturation point (about 35%; Luke and McArthur 1978) from analyses. Where higher fuel moistures have been included, validation statistics were calculated over the full range of observations. The present study used observations from spring to autumn, and consequently, there were a large number of observations where moisture content was high due to rain. For planning prescribed burning, it is useful to be able to predict when fuel will dry sufficiently to become available to burn, and so, exclusion of high moisture content values from our study was not desirable. The presence of high moisture contents meant that naive application of validation statistics could not provide a suitable assessment of model performance, because these statistics would have been dominated by increased variability at higher moisture contents when fuel will not burn, obscuring information about the performance of the model under conditions where fuel will burn.

Table 1. A contingency table for describing the ability of a model to correctly predict whether fuel is flammable.

	Fuel moisture content observation	
Fuel moisture content model prediction	<25%	≥25%
<25%	Hit	False alarm
≥25%	Miss	Correct rejection

Instead, we assessed the model in terms of two criteria: (*i*) can the model predict whether the fuel will or will not burn, and (*ii*) in conditions when the fuel will burn, how accurately does the model predict FMC? In assessing the model against the first criterion, it is necessary to propose an FMC above which the fuel is considered inflammable. For the present study, we use 25%, the moisture content of extinction for forest fuels (Catchpole 2001). This is a conservative value; some forest fuels may extinguish at lower moisture contents, particularly at low wind speeds. This cutoff value is also convenient for assessing the adequacy of the model processes. Moisture contents above about 25% are determined predominantly by processes governing interception and evaporation of rainfall or condensation, whereas those below 25% are determined by vapour exchange processes. Thus, failure against the first criterion indicates problems with treatment of rainfall or condensation while accuracy below 25% describes the adequacy of vapour exchange processes.

The ability of the model to correctly predict whether the fuel was flammable or not can be quantified by dividing observations into four categories, which may be presented as a contingency table (Table 1).

A basic indicator of model performance is the fraction of correct predictions (FC): $(a + b)/(a + b + c + d)$, where a is hits, b is correct rejections, c is misses, and d is false alarms. In a review of the use of contingency tables for assessing numerical weather prediction models Stanski et al. (1989) argue that FC may not give an accurate assessment of model performance because it is dominated by the most common categories. They suggest using a suite of statistics to describe model performance. The probability of detection (POD) is the number of forecast events (FMC < 25%) divided by the number of observed events, POD = $a/(a + c)$. The postagreement (PAG) is the number of correct event

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predictions divided by the number of forecast events, PAG = $a/(a + d)$. An ideal model will have both POD = 1 and PAG = 1, meaning that it will forecast all times when fuel is flammable but will generate no false alarms. A high POD and low PAG indicates that a model has a dry bias, and low POD and high PAG indicates a wet bias. Model bias can be quantified as the number of forecast events divided by the number of observed events, bias = $(a + d)/(a + c)$. Bias >1 indicates a dry bias in the model. A robust description of model performance is given by the critical success index (CSI), the number of correctly forecast events divided by the total number of events forecast and (or) observed, CSI = $a/(a + c + d)$. CSI is a relative measure and is used to compare different models, with values closer to 1 indicating better performance.

Model performance against the second criterion can be assessed by calculating validation statistics such as ME, MAE, and RMSE for data points where both observation and prediction are below 25% (hits in Table 1). The exclusion of data points where the model is either too wet or too dry avoids distortion of the validation statistics by scattered values where the model has already been shown to fail.

Field observations

Fuel moisture and basic weather observations were made from October 1983 to March 1984 in two forest types. The field program was designed to test the empirical fuel moisture model described in Sneeuwjagt and Peet (1998), which requires only daily temperature, humidity, and rainfall observations to run, and so, very minimal weather observations were made. If an experiment were designed specifically to test our model, the field program would be regarded as inadequate as several quantities required were not measured on site. To make use of the unique set of fuel moisture data, we have used proxy data and simulations to estimate weather variables which were not measured (see the Simulation of boundary conditions section).

Fuel moisture

Fuel moisture was measured in stands of jarrah (*Eucalyptus marginata* Sm.) and karri (*Eucalyptus diversicolor* F. Muell.) forest located 30 km west of Manjimup in southwestern Western Australia (34°15′S, 116°00′E) that were 3 km apart from one another. The stands were selected as being representative of mature forest stands of each type. The overstorey in the jarrah forest was 25–30 m in height and had a basal area of 25 $m^2 \cdot ha^{-1}$. Understorey vegetation was less than 1 m in height and relatively open. Common species included *Hovea elliptica* (Sm.) DC., *Leucopogon verticillatus* R. Br., and *Podocarpus drouynaianus* F. Muell. The karri stand had an overstorey 50 m in height with a basal area of 45 $m^2 \cdot ha^{-1}$. The understorey was dominated by *Bossiaea aquifolium* Benth. up to 5 m in height. Both stands were in a midslope position with a slight westerly aspect.

The moisture content of the litter fuel in each stand was determined daily at 08:00 and 14:00 by collecting samples from undisturbed areas of the litter bed. At both stands, three samples of surface litter and profile litter were collected. Surface litter is the top 10 mm of the litter layer, and profile litter is the entire litter layer down to the mineral soil. The litter layer was 20 mm deep in the jarrah forest and 35 mm deep in the karri forest. Litter samples were sealed in tins and returned to the laboratory to be weighed, oven-dried for 18 h at 102 °C, and then reweighed to determine moisture loss. The initial moisture content of each sample was calculated and then averaged for all samples. Field sampling commenced on 12 October 1983 and continued until 16 March 1984. Fuel moisture is frequently very variable, particularly in wet conditions, and three samples may not be adequate to accurately estimate mean moisture content. For future studies, we recommend an increased number of samples be made.

Weather

Basic weather observations were made at a site midway between the two forest stands. Temperature and relative humidity were recorded by a thermohygrograph in a standard instrument shelter located in a recently logged open area. Daily minimum and maximum air temperature and minimum relative humidity were tabulated manually from thermohygrograph records. A rain gauge located at this site was read daily at 08:00 to the nearest 0.1 mm. It is possible that there was some variation in temperature and humidity between the instrument location and sampling sites because of increased solar radiation reaching the ground in the cleared area. An observational study of temperature and humidity gradients between a car park and an oak forest (Miller 1980) found that gradients were negligible on windy days but air in the forest could be up to 3 °C cooler and humidity 10% higher on calm days. Differences in the present study would be expected to be smaller than was the case with a sealed car park, as the ground surface in the clearing would allow greater conversion of net radiation to latent heat, reducing heating and increasing humidity. Nevertheless, on the few calm days during the study period (Fig. 1), air temperature may have been overestimated and humidity underestimated in the observations. With the limited observations available, it was not possible to detect or correct for such an error.

Wind speed was not measured at the sampling site. Twice daily (09:00 and 15:00) wind speed observations were obtained from the Bureau of Meteorology weather observation station at Pemberton (34°27′S, 116°3′E), 25 km from the fuel moisture sampling site.

Modelling

The fuel moisture model

The model used to predict fuel moisture has been described in detail by Matthews (2006). The model represents fluxes of energy and water in a litter bed composed of three materials: litter, air, and free liquid water on the surfaces of the litter. The litter bed is bounded above by the atmosphere and below by the soil. The model has one spatial dimension: height. The properties of the litter bed are assumed to be horizontally homogeneous, and no horizontal transport is included. The heat and water budget of each of the three materials is calculated at five equally spaced nodes within the litter layer using equations for six quantities: (*i*) T_m, litter temperature (K); (*ii*) T_l, the temperature of free liquid water on the litter surfaces (K); (*iii*) T_a, air temperature (K); (*iv*) m,

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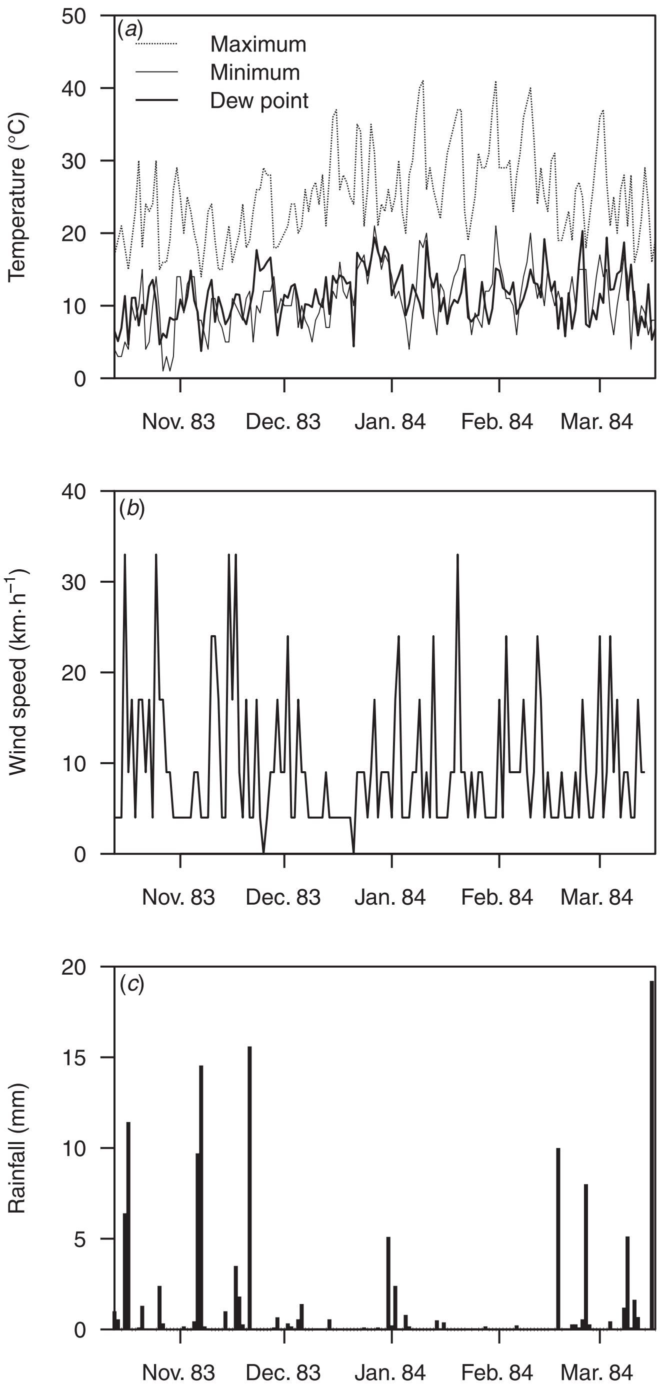
Fig. 1. Weather observations: (*a*) maximum and minimum air temperature and dew point, (*b*) wind speed at 15:00 measured at 10 m height in the open, and (*c*) daily rainfall totals measured at 08:00.



litter moisture content (kilograms of water per kilogram of dry litter); (*v*) *l*, amount of liquid water on litter surfaces (kilograms of water per cubic metre of litter bed); and (*vi*) *q*, specific humidity (kilograms of water vapour per kilogram of air).

Physical processes that change these six quantities are represented in the model as fluxes of energy and water among the three materials at a given level, among levels within a given material, and between the litter layer and the atmosphere or soil. Fluxes are computed using physical principles or from laboratory derived regression equations for processes where a physical description is unavailable or too complex.

Fluxes of heat, water, and radiation between the litter layer and the soil or atmosphere were computed from boundary conditions: air temperature, wind speed, specific humidity, rainfall rate, solar radiation, thermal radiation, soil temperature, and soil moisture. The equations were solved numerically using a 1 h time step. To allow comparisons with field measurements of surface and profile fuel moisture, the model predictions of litter moisture content and amount of surface water were combined

$$[1] \qquad S = 100 \sum_{i=1}^{M} (m_i + l_i/\rho_{\text{bulk}})$$

$$[2] \qquad P = 100 \sum_{i=1}^{N} (m_i + l_i/\rho_{\text{bulk}})$$

where S is the total moisture content (%) of the top 10 mm of the litter layer, P is the moisture content (%) of the entire litter layer, m_i and l_i are the water content of the litter ($kg{\cdot}kg^{-1}$) and the free water content ($kg{\cdot}m^{-3}$) of the ith model layer, ρ_{bulk} is the litter layer bulk density ($kg{\cdot}m^{-3}$), $N = 5$, and M is the number of layers per 10 mm of litter, a function of layer depth.

The litter layer is described using 26 parameters, which appear in the model equations. The parameters selected were those used for *E. obliqua* forest in Tasmania (Matthews 2006) with two changes. Firstly, measured litter bed depths were used (20 mm in jarrah forest and 35 mm in karri forest). Secondly, the rainfall storage capacity of the litter, D_s, was halved from 1.15 $kg{\cdot}kg^{-1}$, measured by Putuhena and Cordery (1996) at rainfall rates of 48 and 60 $mm{\cdot}h^{-1}$, to 0.58 $kg{\cdot}kg^{-1}$. This change was made in light of the observation by Sato et al. (2004) that D_s at rainfall intensities below 5 $mm{\cdot}h^{-1}$ is approximately half the value at 50 $mm{\cdot}h^{-1}$. The largest daily rainfall amount during the field sampling period was 20 mm, and the majority of falls were less than 1 mm, implying rainfall rates below 5 $mm{\cdot}h^{-1}$.

Simulation of boundary conditions

To run the model, it is necessary to supply values of boundary conditions at 1 h intervals. The boundary conditions required are air temperature, wind speed, specific humidity, rainfall rate, solar radiation, thermal radiation, soil temperature, and soil moisture.

Air temperature was interpolated between observed minima and maxima using the method of Beck and Trevitt (1989), which models daytime temperature using a sine curve with maximum temperature at 15:00 and nighttime temperature using an exponential decay curve.

Midafternoon specific humidity was calculated from maximum air temperature, minimum relative humidity, and standard atmospheric pressure at 200 m height (989 hPa). Hourly values were calculated by linear interpolation between observations. For any values where interpolated specific humidity exceeded saturation specific humidity, the

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interpolated value was reduced to the saturation value to ensure relative humidity remained at or below 100%.

Wind speeds were measured at 10 m height above grass. For use in the forest, the measured wind speeds were scaled to give values corresponding to 1.2 m height under the forest canopy. The ratios used were 3.1:1 for jarrah forest (Knight et al. 1998) and 7:1 for the karri forest (Sneeuwjagt and Peet 1998), which was taller and had a denser understory than the jarrah forest. Wind speed was then interpolated between 09:00 and 15:00 observations by the same method used for air temperature (Beck and Trevitt 1989).

Clear-sky solar radiation was estimated using the model of Bird and Hulstrom (1981), with solar position calculated using methods described in Meeus (1991). The effect of clouds was estimated by comparing the diurnal temperature range on a given day with the climatological mean diurnal temperature range, as described by Thornton and Running (1999). Finally, canopy interception of solar radiation was computed using the Beer law equation:

$$[3] \qquad f = e^{-\gamma\lambda}$$

where f is the fraction of radiation transmitted, γ is the attenuation coefficient, and λ is the leaf area index. Silberstein et al. (2001) reported annual variation in λ from 1.32 in October to 0.88 in March owing to summer leaf shedding but did not measure a corresponding change in solar radiation below the canopy. They suggest this result may be attributed to interception by trunks and branches, variation in diffuse radiation, or variation in leaf angle and reflectance causing deviation from the prediction of the Beer's law (Silberstein et al. 2001). We use $\gamma = 1$ and $\lambda = 1$ in jarrah forest to match eq. 3 to the results of Silberstein et al. (2001) and $\lambda = 1.5$ in the more densely stocked karri forest (Carbon et al. 1979).

Thermal radiation, L, was estimated from air temperature (Monteith and Unsworth 1990):

$$[4] \qquad L_c = 0.98\sigma T_a^4$$

$$[5] \qquad L_a = 213 + 5.5(T_a - 273.15)$$

$$[6] \qquad L = fL_a + (1 - f)L_c$$

where L_c is radiation emitted by the forest canopy (W·m^{-2}), L_a is radiation emitted by the atmosphere (W·m^{-2}), T_a is air temperature at 1.2 m height (K), and σ is the Stefan–Boltzmann constant (5.67×10^{-8} W·m^{-2}·K^{-4}). L_a was multiplied by 1.2 on rainy days to account for increased radiation from low cloud.

Interception of rainfall by the forest canopy was modelled using a daily forest water balance model called SWUF (Paul et al. 2003). SWUF is a cascading-bucket type model that has been successfully applied in eucalyptus native forests in the Australian Capital Territory and Victoria, Australia. An accurate deterministic disaggregation of daily rainfall to hourly rainfall rates was not possible, because information about the time, duration, and intensity of showers cannot be recovered from daily totals. Although sophisticated stochastic disaggregation methods are available (Connolly et al. 1998), preliminary trials indicated that our model predictions were not sensitive to the disaggregation method used. This lack of sensitivity occurred because high overnight relative humidity and low wind speed resulted in very low evaporation rates overnight and, thus, similar morning retention of intercepted rainfall whether the simulated rain fell during the day or overnight. We adopted a simple deterministic method in which rain fell uniformly from 20:00 to 08:00 on days on which rain was recorded. This method was selected on the basis of 3 months of pluviograph data from Pemberton, which indicated a preference for nighttime rain.

The model of Paul et al. (2003) was also used to simulate soil moisture, for which no observations were available. Hourly values were calculated by linear interpolation between daily model values.

In the absence of any suitable observations from the study site, soil temperature was assumed to be equal to air temperature, an assumption which was found to be appropriate in *E. obliqua* forest in Tasmania (Matthews 2004).

The methods described previously required several approximations and assumptions to synthesize boundary conditions from a minimal set of observations. The present study represents a worst-case scenario in terms of available weather observations. Increasing availability of near real time data from automatic weather stations and detailed fire weather forecasts should make specification of boundary conditions less problematic in the future.

Fuel moisture predictions

A fuel moisture model may be used for an extended period without supporting field observations, for example, for monitoring fire danger or identifying suitable periods to conduct prescribed burns or for shorter periods after field observations have been made, that is, to predict fire behaviour during a burn. Two sets of predictions were made to test model performance in both scenarios.

For the first set of predictions the model was initialized with observed surface (SMC) and profile moisture content (PMC) on the first day of the experiment, 13 October 1983. The model was then run in each forest type from the time of the first observations, 08:00 on 13 October 1983, to the time of the last observation 14:00 on 16 March 1984. SMC and PMC predictions were then calculated from the model output using eqs. 1 and 2 at the times corresponding to the observations.

For the second set of predictions, a series of 1, 2, 3, and 4 day model runs were made. Each of the four series of model runs commenced on 14:00 on 13 October 1983. For each of the series, the model was run for the specified number of days, at the end of which SMC and PMC predictions were calculated from the model output using eqs. 1 and 2. The model was then reinitialized with observed fuel moisture, and the prediction process was repeated until 12 March 1984. The use of nonoverlapping forecast periods reduced the number of observations available to calculate error statistics but was required to ensure the independence of the predictions.

Results and discussion

Observations

Weather observations are summarized in Fig. 1. The weather in this region of Western Australia is strongly influenced by the easterly movement of cold fronts along the

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southern coast. The passage of fronts results in regular weather cycles at intervals of 5–10 days, which are characterized by increasingly hot and dry conditions because the direction of the wind changes from southeast to northeast and eventually northwest prior to the passage of the next front (McCaw and Hanstrum 2003). Successive days of high temperature and low humidity may occur towards the end of each cycle during summer and early autumn. Rainfall was recorded on 69 days, with 65% of falls being less than 1 mm. The heaviest daily rainfall was 20 mm. Total rainfall over the experiment was 164 mm. Maximum temperature was above 30 °C on 37 days and above 40 °C on 4 days.

The cycling of wet and dry weather produced a cycle of wetting and drying in FMC, which was superimposed on a seasonal drying trend in spring and early summer (Fig. 2). Although only 3 km apart and thus exposed to almost identical weather conditions, the differences in forest types produced marked differences in FMC. PMC in the karri forest dried much more slowly than in jarrah. The karri profile was first combustible (FMC < 25%) on 8 December 1983, whereas the jarrah profile reached 25% on 15 October 1983 in the first week of the experiment. There were less pronounced differences in SMC, but the jarrah litter was more frequently available for burning than the karri litter. Afternoon SMC was <25% in jarrah and karri on 128 days and 102 days, respectively. It was <10% on 58 days and 25 days, respectively. SMC < 5% was recorded on 2 days in jarrah forest but not at all in karri forest.

Modelling

When run over the entire experimental period, the model correctly reproduces the differences in the drying cycles in the two forest types, in particular the much slower drying of the karri profile in spring (Fig. 2). Although the drying trends in karri PMC were largely correct, there were two periods when the predictions diverged noticeably from observations. These were at the beginning of December 1983, when the model overpredicted an increase in PMC due to rainfall, and at the end of February 1984, when the model failed to predict significant drying between rain on the 18 February 1984 and 25 February 1984. Early in the experiment, modelled karri SMC dried too slowly, remaining above 70%, while the observations were below 50%. The shorter drying cycles in the jarrah were not as well resolved in the observations as in the karri observations; however, the model reproduced the rapid drying, and there were no extended periods of over- or under-prediction of SMC or PMC.

The best correlation between observations and predictions was in karri PMC (R^2 = 0.87). There was more scatter in karri SMC predictions (R^2 = 0.64) and both jarrah SMC (R^2 = 0.67) and PMC (R^2 = 0.74) predictions (Fig. 3). In spite of this scatter, the model correctly predicted whether the fuel was flammable or not 81%–92% of the time (Table 2). There were no strong biases in either SMC or PMC. Bias ranged from 0.91 to 1.13, with values <1 for SMC and >1 for PMC in both forest types. Probabilities of detection and postagreement values ranged from 0.79 to 0.93. Taken together, these statistics imply that the model can be expected to correctly predict whether fuel is or is not flammable 80%–90% of the time.

The CSI was calculated for all predictions, to be used for future comparison with other models, and for afternoon predictions only, to allow comparison with the 1–4 day forecasts, which included only afternoon predictions (Table 2). The CSI of the 1–4 day forecasts did not differ significantly from the whole-of-experiment predictions. The fact that the CSIs of the short forecasts were not different from the original model run indicates that it will produce equally good predictions if it is run with only observed weather for a period of time when observations are not available to initialize the model. The amount of time required will depend on the fuel and the time of year. In dry conditions, only 24 h may be required; however, in heavy fuel in spring (Fig. 2), several months may be required. Because contingency table analysis has not been applied to other FMC models, it is not yet possible to determine how the model performance just described compares with existing models. The stability of the model CSI over the 1–4 day forecasts is in contrast to weather forecasts for which skill typically decreases with the length of the forecast. This result suggests that for operational purposes the maximum useful length of fuel moisture forecasts is limited by the accuracy of weather forecasts rather than by the fuel moisture model.

Conventional statistical analysis for observations where the model correctly determined the flammability of the fuel indicated a dry bias in both jarrah and karri forests (Table 3). These biases meant that only a small fraction of predictions fell within 1% and 2% of observations. The biases and the MAE and RMSE listed in Table 3 are similar to that observed in other studies using uncalibrated models (Viney and Hatton 1989) but are larger than has been achieved for models that were calibrated to observations, for which MAE and RMSE <2% were observed (Catchpole et al. 2001). The accuracy of FMC predictions required for a model to be useful can be assessed by examining the effect of errors in fuel moisture on fire behaviour predictions. By analysing the commonly used model of McArthur (1967), Trevitt (1991) found that for rate of spread predictions to be accurate to within ±50%, SMC needs to be specified to within 2% for SMCs > 8% and 1% for SMCs < 8%. Analysis of the rate of spread function in Burrows' (1994) model for jarrah forest indicates SMC also needs to be specified to within 2% at SMCs > 8% and 1% at SMCs < 8% to achieve the same level of accuracy. Clearly the model does not meet these criteria. This failure is not surprising because the FMC of different species of litter fuels is known to differ by more than 2% under common weather conditions (Anderson 1990), whereas we had available only a generic description of the most important property that determines the moisture content of flammable fuels: the equilibrium moisture content (EMC).

To test the effectiveness of species-specific EMC on model predictions, the parameter estimation methods described in Matthews (2006) were used to estimate EMC by fitting model predictions of SMC to observations where measured SMC was <25% in each forest type. Validation statistics for the calibrated model are listed in Table 3. Calibrating the model removes the bias from SMC predictions (Fig. 4); however, because karri PMC was systematically higher than SMC, there was still a –2% bias for karri PMC

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Fig. 2. Comparison of predicted and observed fuel moisture: (*a*) jarrah surface moisture content (SMC), (*b*) jarrah profile moisture content (PMC), (*c*) karri SMC, and (*d*) karri PMC. The curves are the model predictions, and the points are the observations.

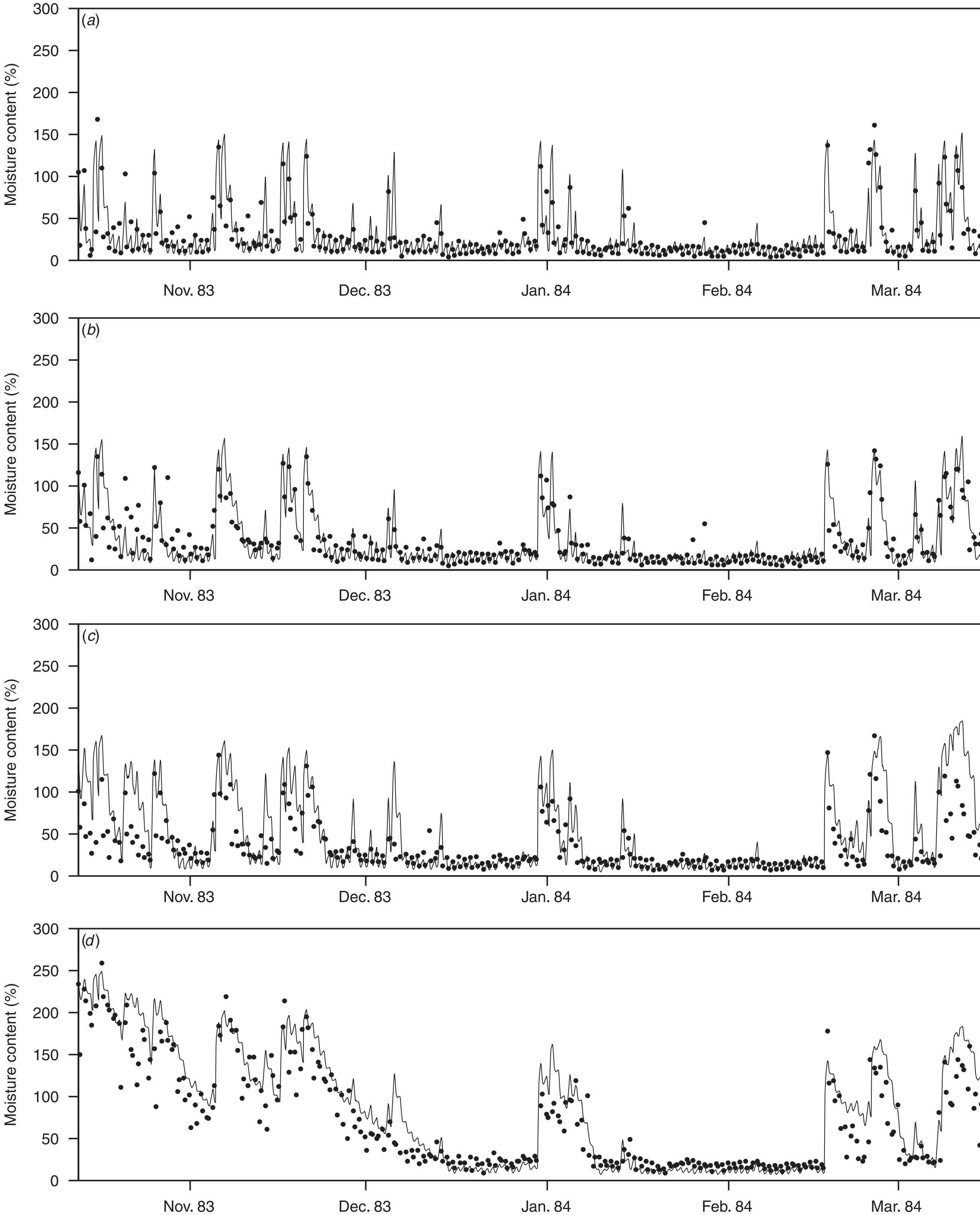

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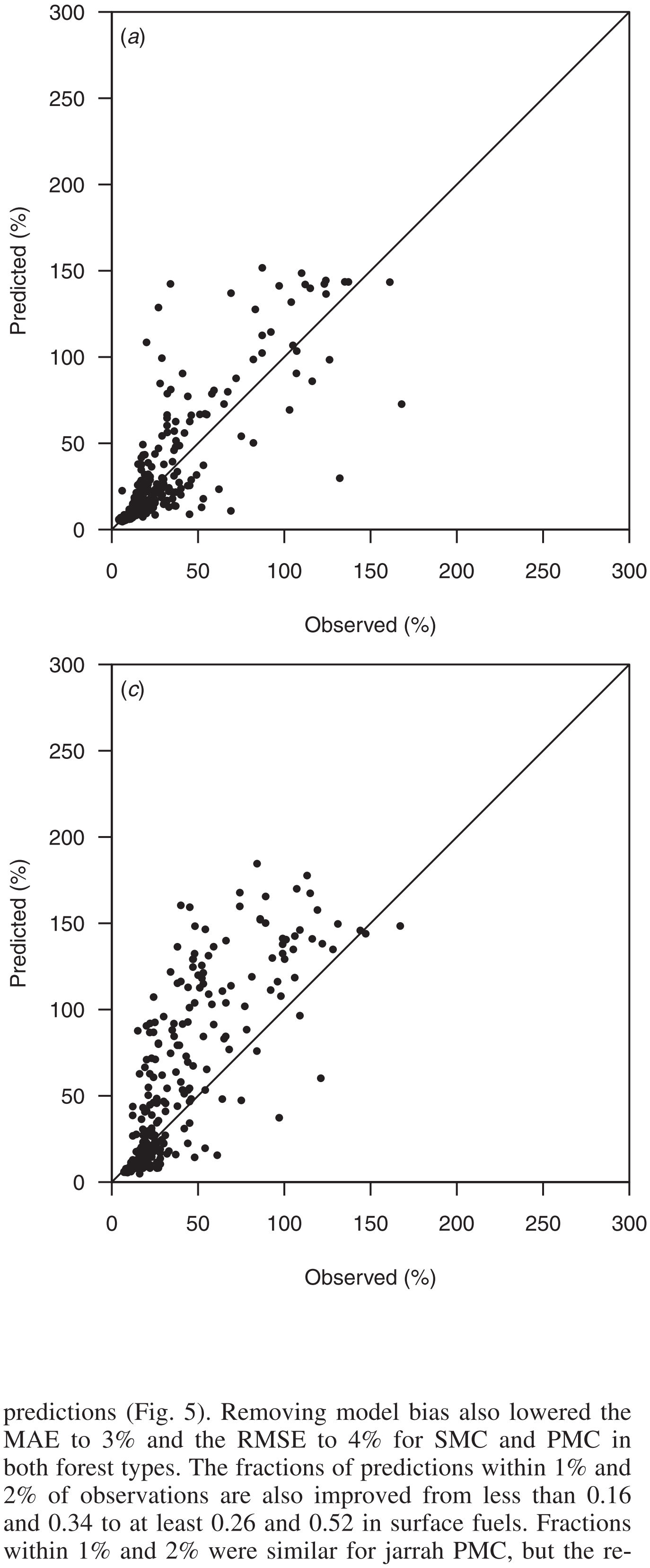
Fig. 3. Comparison of predicted and observed fuel moisture: (*a*) jarrah surface moisture content (SMC), (*b*) jarrah profile moisture content (PMC), (*c*) karri SMC, and (*d*) karri PMC.



predictions (Fig. 5). Removing model bias also lowered the MAE to 3% and the RMSE to 4% for SMC and PMC in both forest types. The fractions of predictions within 1% and 2% of observations are also improved from less than 0.16 and 0.34 to at least 0.26 and 0.52 in surface fuels. Fractions within 1% and 2% were similar for jarrah PMC, but the remaining 2% bias in karri PMC meant that fractions within 1% and 2% remained low at 0.16 and 0.34. Thus, approximately 50% of surface moisture predictions met Trevitt's (1991) and Burrows' (1994) requirement for less than 2% error, and so, further improvement is still desirable. These error statistics were worse than were obtained when the same model was fitted to fuel moisture observations made in conjunction with detailed boundary condition observations (Matthews 2006) but were similar to the statistics reported by Rothermel et al. (1986), who used similarly limited

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Table 2. Contingency table analysis of model predictions of surface (SMC) and profile moisture content (PMC).

	Karri forest		Jarrah forest	
	SMC	PMC	SMC	PMC
Contingency table categories				
Hits	140	95	189	163
Correct rejections	111	188	74	96
Misses	37	13	23	13
False alarms	21	13	21	35
FC	0.81	0.92	0.86	0.84
POD	0.79	0.88	0.89	0.93
PAG	0.87	0.88	0.90	0.82
Bias	0.91	1.00	0.99	1.13
CSI				
Overall	0.71±0.07	0.79±0.08	0.81±0.05	0.77±0.06
Afternoon observations only	0.72±0.09	0.84±0.09	0.87±0.06	0.83±0.07
One-day forecast	0.79±0.08	0.82±0.10	0.90±0.05	0.85±0.07
Two-day forecast	0.70±0.12	0.83±0.13	0.87±0.09	0.89±0.09
Three-day forecast	0.69±0.15	0.75±0.17	0.91±0.09	0.92±0.09
Four-day forecast	0.84±0.14	0.66±0.23	0.79±0.14	0.93±0.11

Note: FC, fraction correct; POD, probability of detection; PAG, postagreement; CSI, critical skill index. Uncertainties are 95% confidence intervals calculated by the bootstrap method (Efron 1979).

Table 3. Statistical analysis of model predictions of surface (SMC) and profile moisture content (PMC) for moisture content <25%.

	Karri forest		Jarrah forest	
	SMC	PMC	SMC	PMC
Matthews (2006) parameters				
ME	–0.03	–0.05	–0.02	–0.02
MAE	0.04	0.06	0.04	0.04
RMSE	0.05	0.06	0.03	0.03
Within 1%[a]	0.09	0.06	0.15	0.19
Within 2%[b]	0.25	0.11	0.34	0.37
Parameters estimated from observations				
ME	0.00	–0.02	0.00	0.00
MAE	0.03	0.03	0.03	0.03
RMSE	0.04	0.04	0.04	0.04
Within 1%[a]	0.26	0.16	0.28	0.26
Within 2%[b]	0.56	0.34	0.52	0.57

Note: ME, mean error; MAE, mean absolute error; RMSE, root mean square error.

[a]Fraction of predictions within 1% of observations.

[b]Fraction of predictions within 2% of observations.

weather observations. Thus, some error may be attributed to limited boundary conditions observations, but model deficiency cannot be ruled out. Possibilities for improvements are discussed in the following.

Conclusions

We have demonstrated that our model can predict with 80%–90% accuracy whether litter fuel is flammable in two types of eucalyptus forest. Model predictions of SMC when the litter was dry enough to be flammable were unbiased once the model had been calibrated against observations; however, only 50% of predictions were within 2% of observed values, which is the accuracy required to make the rate of spread predictions accurate to ±50%. This implies that care is required when using modelled fuel moisture to predict fire behaviour.

Although improvement in prediction of the moisture content of flammable fuels is certainly desirable, our results are similar to those reported for other models currently in operational use (Rothermel et al. 1986; Viney and Hatton 1989). It remains to be seen whether the processed-based modelling approach is better or worse than existing empirical models when both are compared using the same set of observations.

There is the greatest need for improvement in the prediction of fuel moisture content at low values. The differences in prediction error between those reported here and in Matthews (2006) suggest that mean absolute error could be reduced approximately 1% by more accurately specifying boundary conditions. The increased availability of automatic weather station data since our field measurements were made in 1983–1984 has the potential to improve specification of boundary conditions. Making gridded weather forecasts available also has the potential to offer improvements over existing fire weather forecasts, which offer only basic information.

The sensitivity of the model to EMC suggests that further improvement might be possible if separate absorption and desorption equilibrium moisture content curves are used. However, the methods used to simulate boundary conditions meant that humidity was always decreasing at both 08:00 and 14:00 so that the model always used the desorption curve to determine equilibrium moisture content. This should not discourage attempts to supplement the very sparse EMC measurements available for Australian species. Obviating the need for curve fitting to field measurements

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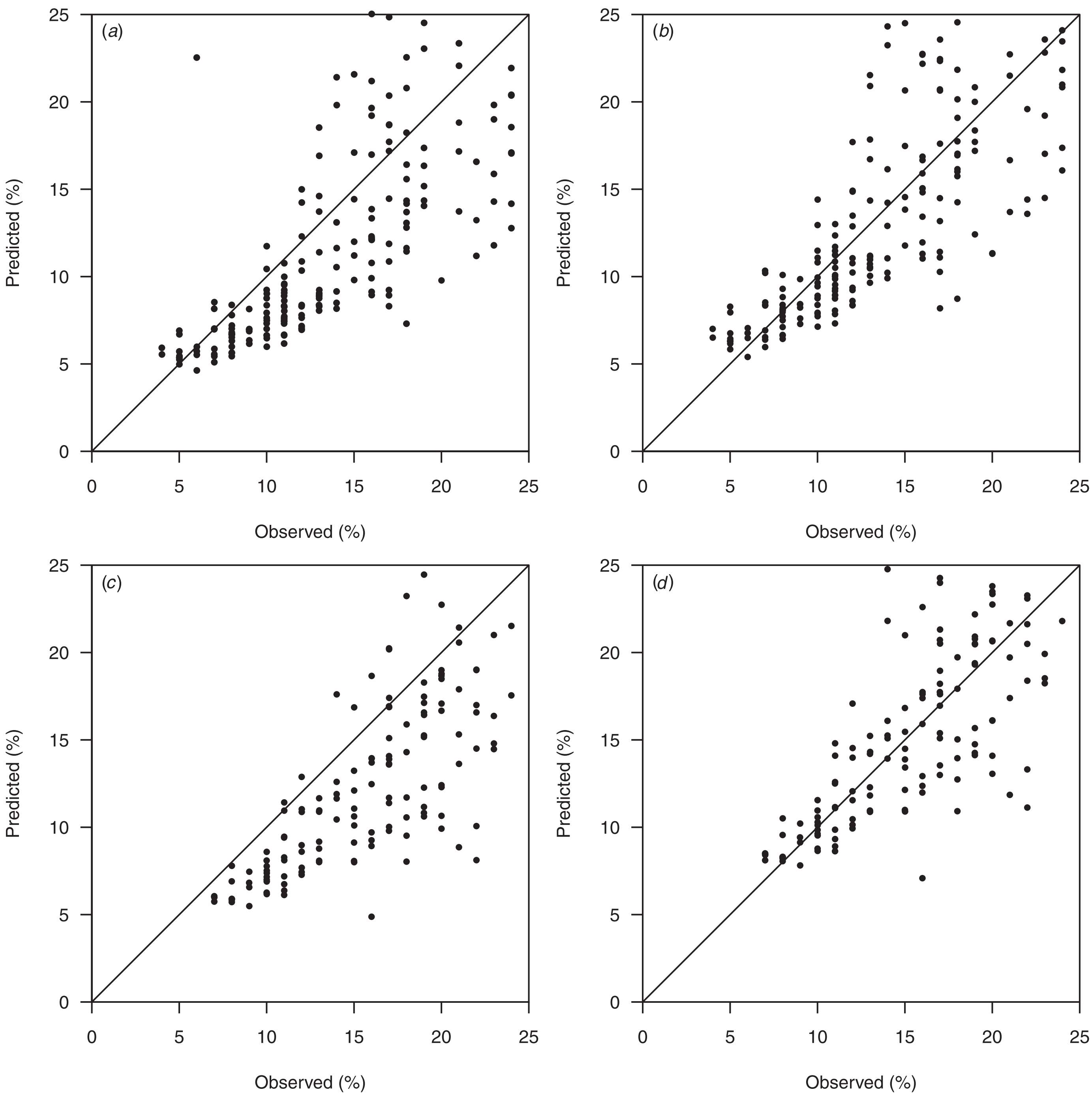
Fig. 4. Comparison of predicted and observed fuel moisture for samples where the surface moisture content (SMC) was observed and predicted to be <25%: (*a*) jarrah SMC, (*b*) jarrah SMC predicted using parameters estimated from observations, (*c*) karri SMC, and (*d*) karri SMC predicted using parameters estimated from observations.



would also allow the identification of other possible weakness in the model, which may be hidden by fitting the model to measurements.

In its present form, the model is suitable for making operational fuel moisture prediction in eucalyptus forest. For accurate fire behaviour predictions to be made in forest types other than jarrah and karri, it will be necessary to conduct a field study to ensure that SMC predictions are unbiased. It ought to be possible to adapt the model to other fuel types (e.g., pine forest or heath)

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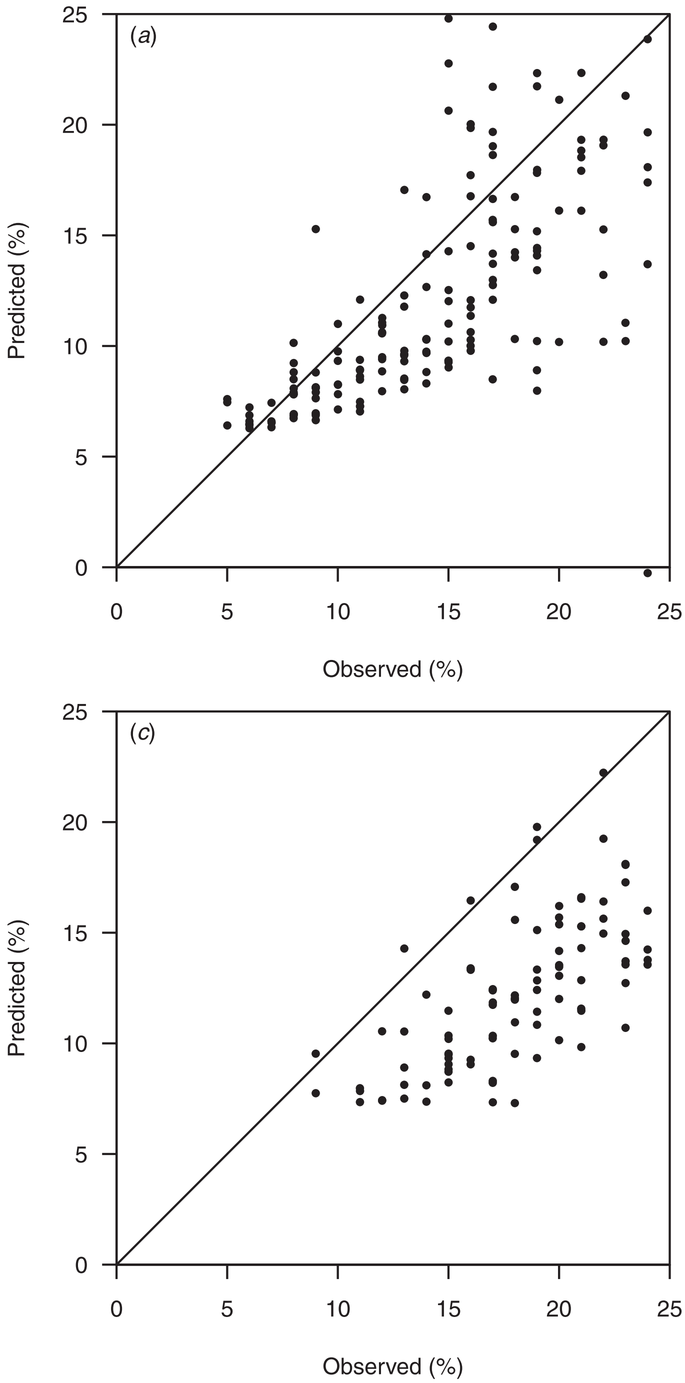
Fig. 5. Comparison of predicted and observed fuel moisture for samples where the profile moisture content (PMC) was observed and predicted to be <25%: (*a*) jarrah PMC, (*b*) jarrah PMC predicted using parameters estimated from observations, (*c*) karri PMC, and (*d*) karri PMC predicted using parameters estimated from observations.



with suitable modification of model parameters. We have yet to demonstrate that the model can correctly account for the effect on fuel moisture of variation in radiation and soil moisture due to varying aspect and slope position. This will be the subject of future research.

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References

Anderson, H.E. 1990. Predicting equilibrium moisture content of some foliar forest litter in the northern Rocky Mountains. USDA For. Serv. Intermountain For. Range. Exp. Stn. Res. Pap. INT-429.

Beck, J.A., and Trevitt, A.C.F. 1989. Forecasting diurnal variations in meteorological parameters for predicting fire behaviour. Can. J. For. Res. **19**: 791–797.

Bird, R.E., and Hulstrom, R.L. 1981. A simplified clear sky model for direct and diffuse insolation on horizontal surfaces. US Department of Energy, Solar Energy Research Institute, Golden, Colo. Tech. Rep. SERI/TR-642-761.

Burgan, R.E. 1987. A comparison of procedures to estimate fine dead fuel moisture for fire behaviour predictions. S. Afr. For. J. **142**: 34–40.

Burrows, N.D. 1994. Experimental development of a fire management model for jarrah (*Eucalyptus marginata* Donn ex Sm.) forest. Ph.D. dissertation, Australian National University, Canberra, Australia.

Carbon, B.A., Bartle, G.A., and Murray, A.M. 1979. Leaf area index of some eucalypt forests in south-west Australia. Aust. For. Res. **9**: 323–326.

Catchpole, W.R. 2001. Fire properties and burn patterns in heterogeneous landscapes. *In* Flammable Australia: the fire regimes and biodiversity of a continent. Cambridge University Press, Cambridge, UK. pp. 49–75.

Catchpole, E.A., Catchpole, W.R., Viney, N.R., McCaw, W.L., and Marsden-Smedley, J.B. 2001. Estimating fuel response time and predicting fuel moisture content from field data. Int. J. Wildland Fire, **10**: 215–222.

Connolly, R.D., Schirmer, J., and Dunn, P.K. 1998. A daily rainfall disaggregation model. Agric. For. Meteorol. **92**: 105–117.

Efron, B. 1979. Bootstrap methods: another look at the jackknife. Ann. Stat. **7**: 1–26.

Gould, J.S. 1994. Evaluation of McArthur's control burning guide in regrowth *Eucalyptus sieberi* forest. Aust. For. **57**: 86–93.

Harrington, M.G. 1982. Estimating ponderosa pine fuel moisture using National Fire-Danger Rating moisture values. USDA For. Serv. Rocky Mountain For. Range Exp. Stn. Res. Pap. RM-233.

Knight, I., Hutchings, P., Cheney, S., and Sullivan, A. 1998. Project Vesta: structure of wind in the forest. CSIRO Forestry and Forest Products, Yarralumla, Australia.

Loomis, R.M., and Main, W.A. 1980. Comparing jack pine slash and forest floor moisture contents and national fire danger rating system predictions. USDA For. Serv. North Cent. For. Range Exp. Stn. Res. Pap. NC-189.

Luke, R.H., and McArthur, A.G. 1978. Bushfires in Australia. Australian Government Publication Service, Canberra, Australia.

Marsden-Smedley, J.B., and Catchpole, W.R. 2001. Fire modelling in Tasmanian buttongrass moorlands: III Dead fuel moisture. Int. J. Wildland Fire, **10**: 241–253.

Matthews, S. 2004. Process-based modelling of fine fuel moisture. *In* Conference Proceedings, Bushfire 2004: Earth, Wind and Fire, 25–28 May 2004, Adelaide, SA, Australia. Department for Environment and Heritage, Adelaide, Australia. [Compact disc.]

Matthews, S. 2006. A process-based model of fine fuel moisture. Int. J. Wildland Fire, **15**: 155–168.

McArthur, A.G. 1967. Fire behaviour in eucalypt forests. Commonwealth of Australia Forestry and Timber Bureau, Canberra, Australia. Leafl. No. 107.

McCaw, W.L. 1998. Predicting fire spread in Western Australian mallee–heath shrubland. Ph.D. dissertation, University of New South Wales, Canberra, Australia.

McCaw, W.L., and Hanstrum, B.A. 2003. Fire environment of Mediterranean south-west Western Australia. *In* Fire in ecosystems of south-west Western Australia: impacts and management. Backhuys Publishers, Leiden, the Netherlands. pp. 87–106.

Meeus, J. 1991. Astronomical algorithms. Willmann-Bell, Richmond, Va.

Miller, D.R. 1980. The two-dimensional energy budget of a forest edge with field measurements at a forest – parking lot interface. Agric. Meteorol. **22**: 53–78.

Monteith, J.L., and Unsworth, M.H. 1990. Principles of environmental physics. Edward Arnold Publishers, London.

Nelson, R.M. 1991. A model of diurnal moisture change in dead forest fuels. *In* Proceedings of the 11th Conference on Fire and Forest Meteorology, 16–19 April 1991, Missoula, Mont. *Edited by* D.F. Potts. Society of American Foresters, Bethesda, Md. pp. 109–116.

Nelson, R.M., Jr. 2000. Prediction of diurnal change in 10-h fuel stick moisture content. Can. J. For. Res. **30**: 1071–1087.

Paul, K.I., Polglase, P.J., O'Connell, A.M., Carlyle, J.C., Smethurst, P.J., Khanna, P.K., and Worledge, D. 2003. Soil water under forests (SWUF): a model of water flow and soil water content under a range of forest types. For. Ecol. Manage. **18**: 195–211.

Plucinski, M. 2004. Testing fuel moisture models in heathlands. *In* Conference Proceedings Bushfire 2004: Earth, Wind and Fire, 25–28 May 2004, Adelaide, SA, Australia. Department for Environment and Heritage, Adelaide, Australia. [Compact disc.]

Pook, E.W. 1993. Empirical models evaluated for prediction of fine fuel moisture in Australian *Pinus radiata* plantations. N.Z. J. For. Sci. **23**: 278–297.

Putuhena, W.M., and Cordery, I. 1996. Estimation of interception capacity of the forest floor. J. Hydrol. **180**: 283–299.

Rothermel, R.C., Wilson, R.A., Jr., Morris, G.A., and Sackett, S.S. 1986. Modeling moisture content of fine dead wildland fuels: input to the BEHAVE fire prediction system. USDA For. Serv. Intermountain For. Range Exp. Stn. Res. Pap. INT-359.

Sato, Y., Kumagai, T., Kume, A., Otsuki, K., and Ogawa, S. 2004. Experimental analysis of moisture dynamics of litter layers — the effects of rainfall conditions and leaf shapes. Hydrol. Process. **18**: 3007–3018.

Silberstein, R., Held, A., Hatton, T., Viney, N.R., and Sivapalan, M. 2001. Energy balance of natural jarrah (*Eucalyptus marginata*) forest in Western Australia: measurements during spring and summer. Agric. For. Meteorol. **109**: 79–104.

Simard, A.J., and Main, W.A. 1982. Comparing methods of predicting jack pine slash moisture. Can. J. For. Res. **12**: 793–802.

Simard, A.J., Eenigenburg, J.E., and Blank, R.W. 1984. Predicting fuel moisture in jack pine slash: a test of two systems. Can. J. For. Res. **14**: 68–76.

Sneeuwjagt, R.J., and Peet, G.B. 1998. Forest fire behaviour tables for Western Australia. Department of Conservation and Land Management, Perth, Australia.

Stanski, H.R., Wilson, L.J., and Burrows, W.R. 1989. Survey of common verification methods in meteorology. World Meteorological Organization, Geneva. WMO World Weather Watch Tech. Rep. No. 8. WMO/TD No. 358.

Thornton, P.E., and Running, S.W. 1999. An improved algorithm for estimating incident daily solar radiation from measurements

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of temperature, humidity, and precipitation. Agric. For. Meteorol. **93**: 211–228.

Trevitt, A.C.F. 1991. Weather parameters and fuel moisture content: standards for fire model inputs. *In* Proceedings of the Conference on Bushfire Modelling and Fire Danger Rating Systems, 11–12 July 1991, Yarralumla, ACT, Australia. *Edited by* N.P. Cheney and A.M. Gill. CSIRO Division of Forestry, Yarralumla, Australia. pp. 157–166.

Viney, N.R., and Hatton, T.J. 1989. Assessment of existing fine fuel moisture models applied to *Eucalyptus* litter. Aust. For. **52**: 82–93.

Weise, D.R., Fujioka, F.M., and Nelson, R.M., Jr. 2005. A comparison of 3 models of 1-hr timelag fuel moisture in Hawaii. Agric. For. Meteorol. **133**: 28–39.

Wotton, B.M., Stocks, B.J., and Martell, D.L. 2005. An index for tracking sheltered forest floor moisture within the Candian Forest Fire Weather Index System. Int. J. Wildland Fire, **14**: 169–182.

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