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Evaluating models to predict daily fine fuel moisture content in eucalypt forest

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ABSTRACT

Two models were evaluated for predicting dead fine fuel moisture content on sites in dry and damp eucalypt forests in Tasmania on a daily basis. Models were based on modifications of the Canadian Fine Fuel Moisture Code, and the process-based model of (Matthews, 2006) with and without modifications to better fit the data. All three models predicted well on the dry site, with little to choose between the two modified models. The process-based model performed better on the damp site. Site differences in moisture content could be explained by differences in vegetation and canopy cover. The ability of the models to predict conditions suitable for prescribed burning was tested. The modified Canadian model resulted in more correct predictions of optimal burning conditions than the process-based models. The modified process-based model gave the most predictions that would falsely indicate conditions were suitable for prescribed burning.

1. Introduction

The moisture content of dead fine fuels has an important role in fire behaviour through controlling fuel flammability, rate of spread, fuel availability, and fire intensity. Predicting fuel moisture content is very important to fire and land managers, as it enables better prediction of current and potential fire behaviour which is required for bushfire response readiness and for conducting planned burning.

Fuel moisture content is the percentage by weight of free and absorbed water in the fuel, and is normally expressed as the percentage of water per oven dry weight of fuel (Viney, 1991). In the absence of precipitation, dead fine fuels (i.e. plant material less than 6 millimetres in diameter) have moisture contents between 3% and 35% (Berry and Roderick, 2005). This upper limit is known as the fibre saturation point and is the moisture content reached at 100% relative humidity. When exposed to precipitation water will also be stored in the cell cavities and on the surfaces of the fuel. In this case fuel moisture may reach values as high as 300% (see, for example, the data range for karri profile litter in Matthews et al., 2007).

Under drying conditions dead fuels undergo desorption and release moisture to the surrounding environment through evaporation until the vapour pressure in the fuel reaches that of the surrounding air. Once this has occurred the fuel is considered to be at its equilibrium moisture content (EMC) (Merrill and Alexander, 1987). Similarly, when the fuel moisture content is below EMC the fuel adsorbs moisture from the air. The drying or wetting rate of a dead fuel particle can be summarised by its response time, which is the time required for it to lose or gain about two-thirds (63%) of the difference between its initial moisture content and its equilibrium moisture content (Merrill and Alexander, 1987). Rates of wetting and drying are determined by the chemical and physical characteristics of the fuel and by weather conditions (Viney, 1991; Matthews, 2013; Slijepcevic et al., 2013). Currently there is a good understanding of the processes that drive FMC but no model has been identified as suitable for resolving spatial variation due to topography or forest structure (Matthews, 2013).

The primary aim of this paper is to test and develop models for predicting dead fuel moisture content for operational fire management in Eastern Australian dry and damp eucalypt forests. Models for predicting dead fine fuel moisture content (FMC) in dry conditions were tested and calibrated in Slijepcevic et al. (2013). This

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paper considers models for predicting FMC in both dry conditions and after rain, and determines how well these models can predict conditions for prescribed burning. Two models were selected to represent the process-based (Matthews, 2006) and empirical (Van Wagner and Pickett, 1985) approaches to modelling FMC.

2. Methods

2.1. Data collection, site location and vegetation community description

Two sites on the lower foothills of Mt Wellington in Tasmania (42°53′28″S, 147°16′28″E), located within 750 m of each other, but one in damp and one in dry sclerophyll forest, were used in the study. Two flat areas on these sites were used to make the daily observations used in this analysis. The lower slopes of Mount Wellington are mostly dominated by *Eucalyptus obliqua* or *Eucalyptus tenuiramis*, or an association between these species. Although the underlying rock is predominantly Permian mudstone, dolerite talus and Triassic sandstone sites are also present (Johnson, 1994).

The damp site has a vegetation community consisting of *E. obliqua* open-forest /tall open-forest over narrow-leaved shrubs (type Eo/S from Johnson, 1994). This *E. obliqua* community occurs on two types of sites, the first on dry or exposed slopes at the upper (altitudinal) range of *E. obliqua* and the second on lower more sheltered or moist sites, such as the site used in this study. Sedges or bracken (*Pteridium eculentum*) commonly dominate the ground layer. This community represents a transition zone between dry and wet sclerophyll forest and can be described either as a shrubby *E. obliqua* forest (Duncan and Brown, 1985) or an *E. obliqua–Olearia lirata–Pultenaea juniperina* wet sclerophyll forest (OB010) (Kirkpatrick et al., 1988).

The dry site has a vegetation community consisting of *E. obliqua–E. tenuiramis* open-forest over shrubs-heath (type Eo-Et/S-H from Johnson, 1994). This community represents a transition from *E. tenuiramis* forest over heath (type Et/H from Johnson, 1994) to an *E. obliqua* forest over heath (type Eo/H from Johnson, 1994). In this community, *Pteridium esculentum* often dominates the ground layer, however many sites are bare, such as the one in this study. It is best described as a shrubby *E. obliqua (E. obliqua–E. tenuiramis)* forest (Duncan and Brown, 1985).

Daily data was collected in the summers of two years, 2002/2003 and 2003/2004. In the first year, the sampling started on 18/12/2002 and concluded on 29/04/2003, while in the second year sampling commenced on 4/11/2003 and concluded on 8/03/2004. This paper uses data from a subset of days (5/01/2004 to 10/02/2004) when solar radiation measurements were made on site.

2.2. Field measurements

2.2.1. Weather measurements

WeatherMaster 2000 (Environdata, QLD, Australia) portable weather stations measuring temperature, humidity, and wind speed were installed on the sampling sites. Solar radiation was measured using Li-200 silicon pyranometers (LiCor, NE, USA). Half-hourly readings of temperature, relative humidity, wind speed and radiation were available for the sampling period. Data were missing on the damp site for a period of about 7 days when the site meteorological station failed. Regression models with autoregressive-moving average error terms were fitted using the relevant dry site variable as the independent variable, and the missing wet site data were predicted from these models (see Makridakis et al., 1998 for details). Estimation of missing data for the damp site had little effect on results as the relevant period (27/01/04 to 4/02/04) was during a very wet period when very few measurement of fuel moisture content were able to be made. Rainfall could be assumed to be reasonably similar on both sides during that period as the sites were only a few hundred metres apart.

2.2.2. Moisture content sampling

Dead fuel moisture content was collected on each of the sites once daily between 12:00 and 14:00. In all there were 27 days of moisture content data, as samples were not collected in the rain. Samples were collected from dispersed locations within these sites.

Dead-fuel moisture samples were taken from bark and litter. Near-surface samples were only collected on the damp site, as there was negligible near-surface fuel on the dry site. (Near-surface fuel is a loose mixture of bark, dead leaves and grass above the litter which is described in McCaw et al., 2012.) The litter samples were collected as two separate samples: one being from the whole profile and the other from the top centimetre of the litter. Elevated bark fuel moisture was sampled at a height of about 1.5 m. Each dead-fuel moisture sample was made up from three to five sub-samples of the bark (*E. Obliqua*) and top litter and three sub-samples of the profile, each of which had a field weight of about 10–15 g. This material was sealed in metal tins for transport back to the laboratory. The field weight of samples was determined as soon as practicable following collection. Oven-dry weights were obtained after drying samples to constant weight at 105 °C (Matthews, 2010).

2.2.3. Fuel characteristics

Fuel hazard scores in the range (0, 4) which describe the amount and arrangement of fuel present on the basis of visual assessment (Gould et al., 2011) were estimated on the sites for each fuel stratum based on the methods given in Marsden-Smedley and Anderson (2011). Fuel loading was estimated from these scores using interpolation of Tables 9.2 and 9.3 in Hines et al. (2010).

2.3. FMC models

2.3.1. The Canadian Fine Fuel Moisture Code

The Canadian Forest Fire Weather Index System (Van Wagner, 1987) predicts the moisture content of three main layers of dead forest floor fuels and combines these with the influence of wind speed to estimate fire behaviour potential. The system uses Canadian mature jack (*Pinus banksiana*) and lodgepole (*Pinus contorta*) pine stands on level terrain as its reference fuel type. It comprises six numerical ratings – three fuel moisture codes and three fire behaviour indices. For each of the codes, moisture is added after rain and reduced after each day's drying. Higher values of codes correspond to lower moisture contents. All codes have built-in time lags and rainfall thresholds (below which precipitation will not lower the value). The system uses standard, daily weather inputs of noon temperature, relative humidity, wind speed and rainfall accumulation.

The Canadian Fine Fuel Moisture Code (FFMC) represents the moisture content of fine surface litter and other fine fuels on the forest floor, and indicates ignition potential. It is based on the value of the previous time step's moisture content, the current EMC, the response time and the rainfall in the timestep. The FWI System calculates outputs daily at 12:00 local standard time (LST), to represent conditions during the peak afternoon burning period of around 16:00 LST (Van Wagner and Pickett, 1985). There are also methods in place to compute outputs on an hourly basis that provide more current estimates of fire potential (Van Wagner, 1977; Alexander et al., 1984; Lawson et al., 1996). A complete description of the FFMC is contained in Van Wagner (1987).

The hourly FFMC is calculated by determining the EMC under drying (E_d) and wetting (E_w) conditions. Drying (k_d) and wetting

(k_w) rates are calculated based on temperature, relative humidity and wind speed. Moisture content (m) is then calculated from EMC, the previous hour's moisture content (m_0) and either k_d or k_w. This value of m is converted to FFMC code form. Moisture is added to m_0 when rainfall occurs (Van Wagner, 1977; Alexander et al., 1984; Lawson et al., 1996).

2.3.2. The Catchpole et al. (2001) model

The model in Catchpole et al. (2001) is similar to the hourly version of the FFMC in that it is based on diffusion theory for a fine particle, so that the rate of change of moisture content depends on the difference between the present moisture content and the equilibrium moisture content (E) and on the response time (τ). Following Nelson (1984) the EMC is linearly related to the logarithm of the Gibb's free energy, ΔG, so that

$$E = a + b\log\Delta G = a + b\log\left(-\frac{RT}{M}\log H\right), \quad (1)$$

where a and b are constants specific to a fuel type and also vary depending on whether the fuel is adsorbing or desorbing moisture, T is fuel temperature (K), H is the relative humidity at fuel level (expressed as a fraction), R is the universal gas constant (1.987 cal K^{-1} mol^{-1}), M is the molar mass of water (18.0153 g mol^{-1}), and log is the natural logarithm. The moisture content at time $t_i = t_{i-1} + \delta t$ (where δt is a small time period) is then predicted from the moisture content at time t_{i-1}, the response time, and the EMC at times t_{i-1} and t_i. The equation given in Catchpole et al. (2001) is

$$m_i = \lambda^2 m_{i-1} + \lambda(1-\lambda)E_{i-1} + (1-\lambda)E_i, \quad (2)$$

where m_i and m_{i-1}, E_i and E_{i-1} are moisture contents and EMCs at times t_i and t_{i-1} respectively and $\lambda = \exp(-\delta t/2\tau)$. However, Eq. (2) is only valid if τ can be assumed constant. In the present study this assumption is not valid when the fuel is drying after rainfall, so the FFMC methodology is used instead, namely,

$$m_i = E_i + (m_{i-1} - E_{i-1})\exp(-\delta t/\tau_i), \quad (3)$$

where τ_i is the response time applicable to absorption or desorption and depends on the current moisture content and environmental variables. See Section 2.3.3.3 for details.

2.3.3. Modification of the Canadian hourly FFMC

The Canadian code was designed for pine litter with a fairly slow response time, especially after rain. It has been modified by Anderson and Anderson (2009) for use in *Ulex europaeus* (gorse) and by Wotton (2009) for use in grasslands. The basic modifications used here were (i) use of a half-hour time period for δt, (ii) use of fuel (rather than screen level) temperature and relative humidity, (iii) changes in formulation of equilibrium moisture content, (iv) changes in the equation for response time and (v) change of rainfall effect. The modifications are described in detail below.

2.3.3.1. Fuel temperature and relative humidity. The litter surface temperature was predicted using a modified version of the equation given by Byram and Jemison (1943)

$$T_f = T_a + \frac{\gamma K}{42.5u_f + 32.7}, \quad (4)$$

where T_a and T_f are the air and fuel temperature, respectively (°C), K is the downward flux of solar radiation (W m^{-2}), u_f is the 2 m wind speed (m s^{-1}) and γ is a constant equal to 0.2. In Byram's formulation the constant, γ, is unity. The profile litter temperature was predicted to be 0.96 times the air temperature. These predictors of surface and profile temperatures were determined by comparison with measured fuel temperatures (see Slijepcevic et al., 2013). The average of the air and predicted litter temperatures was used for the bark and near-surface fuel.

Fuel level relative humidity was predicted from the equation given in Byram and Jemison (1943)

$$H_f = H_a \exp[0.059(T_a - T_f)] \quad (5)$$

where H_a and H_f are ambient and fuel humidity, respectively. As T_f is generally greater than T_a in the daytime, H_f is generally less than H_a. Fuel humidity predicted from Eq. (5) was used for the top litter, the average of ambient and predicted fuel humidity was used for the bark and near-surface fuel, and ambient humidity was used for the wetter profile.

2.3.3.2. Equilibrium moisture content. Eq. (1) was used for the EMC. For simplicity the values of a and b were taken from Cruz et al. (2010) which were shown to work well for predicting the hourly FMC in this fuel type in Slijepcevic et al. (2013). The same values were used for adsorption and desorption. These are the same values as are used in the Matthews (2006) model, a description of which is given in Section 2.3.4.

2.3.3.3. Response time. When the moisture content was above 30% and drying after rain, following Wotton (2009), a scaled drying rate in the Canadian hourly equation was used. The equation for k_d, the inverse of the drying response time (in hours), is

$$k_d = \alpha\log(10)\exp(0.0365T)\left[0.424(1-H^{1.7}) + 0.0694U^{0.5}(1-H^8)\right], \quad (6)$$

where T is fuel temperature (°C), U is screen level wind speed (km/hr), and H is fuel level relative humidity (RH) expressed as a fraction. For adsorption H is replaced by $1 - H$. The value of α for pine needles, in the FFMC calculation, is 0.0579. To fit the data for eucalyptus this was allowed to vary.

The changeover from desorption to adsorption conditions followed the approach of Van Wagner (1977). When the predicted FMC is greater than the desorption EMC the desorption EMC is used to predict the moisture content for the next time period, when it is less than the adsorption EMC the adsorption EMC is used, and when it lies between the adsorption EMC and the desorption EMC the predicted moisture content for the previous time period is used.

A time period of half an hour was used for δt, as this was the minimum time period available from the data. Following Matthews (2006) a response time of 1 h was used when the predicted moisture content for the previous half hour was less than or equal to 25%. When the predicted moisture content for the previous half hour was greater than or equal to 30% the response time was obtained from the modified Canadian equation. When the predicted moisture content in the previous half hour was between 25% and 30% the response time was assumed to vary linearly between the two values. This was done to give continuity both for the minimisation procedure to determine the parameters and to model a change in the physical drying process from evaporation of moisture from between the plant cells to desorption of moisture from within the cells.

2.3.3.4. Rain effect. For the rain effect Wotton (2009) uses

$$m_r = m_0 + 100r/w \quad (7)$$

where m_r is the moisture content after rainfall, m_0 is the moisture content before rainfall, r is the amount of rain (mm) and w is the fuel load (kg/m^2). If m_r is greater than 250% it is set equal to 250%. The rainfall effect thus decreases with increasing load, and thus ability to retain moisture. This formulation caused problems and was modified by adapting the equation used in the daily FFMC calculation, so that

$$m_r = m_0 + \beta(r/w)\exp(-100/(251 - m_0))(1 - \exp(-6.93/r_c)), \quad (8)$$

where r_c is the rain in the previous 24 h and β is a constant to be determined. Thus the rainfall effect also decreases with increasing rain amount and with increasing initial moisture content. No rain threshold was considered as the rain gauge was below the canopy. Determination of the constants α and β complete the implementation of the 'modified Canadian model'.

The rain effect was calculated as if the rain occurred at the end of the time period, unlike the implementation by Wotton (2009) where the predicted moisture content is adjusted for rainfall at the beginning of the time period. Calculating the rain effect at the end of the time period, rather than at the beginning was implemented simply because it produced a slightly better model. There does not seem to be a compelling reason for either choice.

2.3.3.5. Fitting the parameters. The model was fitted to the moisture content data from the bark, litter and profile strata at both dry and damp sites simultaneously. The constants were such that α and β varied with strata but were the same for the same strata on both sites. The constants were determined by minimizing the sum of squares of the errors (SSE) weighted by the reciprocal of the margin of error calculated from the individual moisture content samples.

2.3.4. The Matthews (2006) model

The model given in Matthews (2006) ('Matthews model') is a process-based model that represents fluxes of energy and water in a litter bed composed of three components: 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 heat and water budget of each of the three components is calculated at five equally spaced positions within the litter layer using equations for six quantities: litter temperature, the temperature of free liquid water on the litter surfaces, air temperature, litter moisture content (kg water per kg of dry litter), amount of liquid water on litter surfaces (kg of water per m of litter bed), and specific humidity. Physical processes that change these six quantities are represented in the model as fluxes of energy and water between the three materials at a given level, between levels within a given material, and between the litter layer and the atmosphere or soil. Fluxes of heat, water, and radiation between the litter layer and the soil or atmosphere are predicted by integrating the model energy and water equations using specified boundary conditions. The boundary conditions required are: air temperature, wind speed, specific humidity, rainfall rate, solar radiation, thermal radiation, soil temperature, and soil moisture.

A modification of the original model was used for suspended fuel (Matthews and McCaw, 2006). The suspended fuel model uses the same physical processes as the litter model except that air temperature, humidity, and wind speed are identical to the screen level values and the model has only a single layer. The main consequence of this modification is that fuel temperatures are often lower than litter temperatures during the day, and fuels dry more rapidly after rain than in the litter model (Cruz et al., 2010).

The Matthews model was run with the same parameters as in Slijepcevic et al. (2013). For the litter the same set of parameters were used for both sites and for both surface and profile (since they come from different parts of the same model). A separate set of parameters were used for bark and suspended fuel. A modified form of the model was also tried ('Modified Matthews model') with parameters fitted to the data. Parameters selected for fitting were those which were known to affect wetting and drying and about which there was some uncertainty of the correct value, either because there is variation within the litter (e.g. characteristic litter fragment size) or because no measurements were available (e.g. wetting rates of *E. obliqua* bark). The fitted parameters were fuel characteristic length, litter bulk density, fuel surface-area to volume ratio, EMC parameters, response time, saturation moisture content, wetting rate, and surface water storage capacity. Parameters were fitted by minimising the SSE over all observations weighted by the reciprocal of the margin of error calculated from the individual moisture content samples.

2.3.5. Model assessment

Standard errors for the parameters for the modified Canadian model were determined by bootstrapping the residuals and reconstructing new data, then refitting the model (see Efron and Tibshirani, 1993). As the residuals increased with higher moisture contents the multiplicative residuals (observed values divided by fitted values) were used as a basis for the bootstrap samples.

The models were assessed firstly by using the root mean squared error (RMSE), mean absolute error (MAE) and the mean bias error (MBE) (Willmott, 1982). The RMSE and MAE give estimates of combined bias and precision, the RMSE being more sensitive to outliers than the MAE. The MBE measures only bias. All statistical analyses were conducted using the statistical package R 3.1.0 (R Core Team, 2014).

For prescribed burning it is critical to predict when the litter is available to burn after a period of rain. Tolhurst and Cheney (1999) state that while fuel reduction may be carried out under very mild weather conditions or in lighter fuels with moisture contents between 9% and 13%, 13–16% is generally suitable for fuel reduction. This is consistent with the recommendations in Sneeuwjagt and Peet (1985) that good prescribed burning outcomes can be achieved when litter moisture contents are between 10% and 16%. According to Tolhurst and Cheney (1999) for litter moisture contents between 16% and 22% burning is difficult to maintain and patchy burns will result. Above 22% the litter is very difficult to ignite. With unknown predicted wind speed and soil dryness index the assumption was made that good fuel reduction would be possible for fuel moisture contents between 11% and 16%, and crews would be sent out when the predicted moisture content was in this range for the period required to complete burning operations. The length of the required window depends on the size of the burn area and

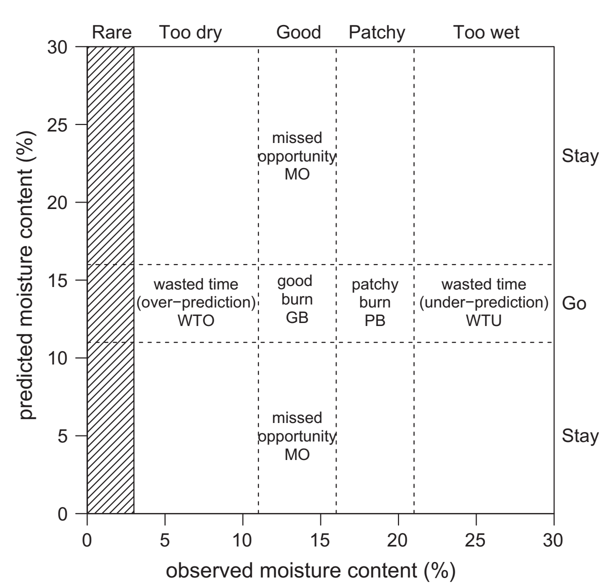

Fig. 1. Diagram of possible outcomes of using predicted moisture content for various observed moisture contents for planning prescribed burning.

ignition method used. Fig. 1 shows the consequence of this strategy for the range of actual moisture contents. A good result is obtained in the region where the predicted and observed moisture contents are in the same range. A patchy burn (PB) is obtained when the crews are sent out but the moisture content is between 16% and 22%. If the moisture content is less than 11% or greater than 22% the crews have wasted time, because of over-prediction (WTO) or under-prediction (WTU). A missed opportunity (MO) occurs when the crews are not sent out even though the moisture content is between 11% and 16%. In all other regions the decision not to send the crews out is correct (though possibly for the wrong reason).

3. Results

The bark hazard scores were estimated to be 2.6 and 3.9 for the dry and wet site respectively. These resulted in estimated fuel loads of 3.6 and 6.9 t/ha respectively. For the profile litter fuel the hazard scores were 3.2 and 3.1 for the dry and wet site respectively, resulting in estimated fuel loads of 13 and 12 t/ha respectively. For the top litter these loads were halved. These loads were used in Eq. (8) to calculate the fuel moisture content after rainfall.

Table 1 gives the minimum, median and maximum moisture contents for the fuel components on each site. The maximums tend, however, to be biased downwards as sampling was not always done on rainy days. Also in the rainy periods the sites were sometimes sampled on different days, as can be seen for the bark sampling in Fig. 3. On the dry site there was no significant difference in median moisture content between bark and litter, using a Wilcoxon two-sample test (Hollander and Wolfe, 1999), but the profile was about 4% wetter than the litter ($p < 0.0001$). Median moisture contents for the bark and litter for the damp site were higher by 4% and 7%, respectively than those for the dry sites, while the median profile moisture content for the damp site was greater by 20% than for the dry site (p-values for all tests were less than 0.0001). The median moisture content for the near-surface fuel on the damp site was not significantly different from that of the bark.

For the modified Canadian model the best fitting constants and the mean and standard deviations of the bootstrap samples are given in Table 2. For α the optimal values were close to the mean of the bootstrap samples, but for β there were large differences which were reflected in the large standard deviations. The standard FFMC model has a response time of 5.72 h at conditions of 26.7 °C temperature, 20% RH and a wind speed of 2 km/h. The grassland model given in Wotton (2009) has a response time of 0.85 h under these conditions. Corresponding response times for the values of α are shown in Table 2 for bark, top litter and profile. For the near-surface fuel, the fitted constants were $\hat{\alpha} = 0.67$ and $\hat{\beta} = 130.4$. The value of $\hat{\alpha}$ corresponds to a response time of 0.5 hr, and the value of $\hat{\beta}$ was much greater than the corresponding value for the profile. Minimization for α for the near-surface fuel was then restricted to be from 0.083 (estimated value for top litter) to 0.39 (corresponding to a response time 0.85 h as used by Wotton (2009) for grass), and for β from 7.463 (estimated value for bark) to 21.41 (estimated value for top litter). Minimised values were then $\hat{\alpha} = 0.39$ and $\hat{\beta} = 21.41$. As the minimised values occurred at the end of these intervals, no standard errors are given.

The time series of fuel moisture contents overlaid with the half-hourly predicted values from the modified Canadian model and

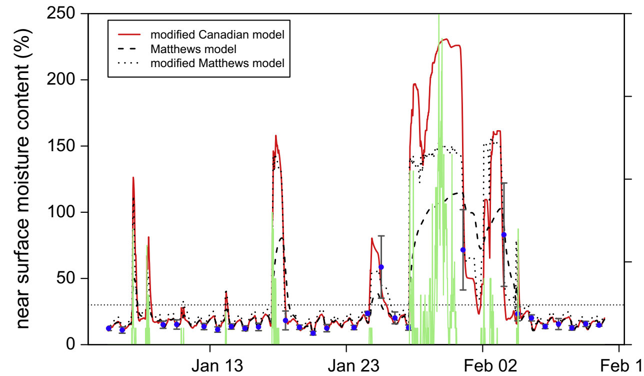

Fig. 2. Time series of the mean FMC for near surface fuel (blue dots) for the damp site. The horizontal dotted line indicates 30% moisture content. 95% confidence intervals for the true FMC values are shown as grey vertical lines with end bars. The modified Canadian model (red), the Matthews model (black dashed) and the modified Matthews model (black dotted) are overlaid. Rainfall is shown in green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

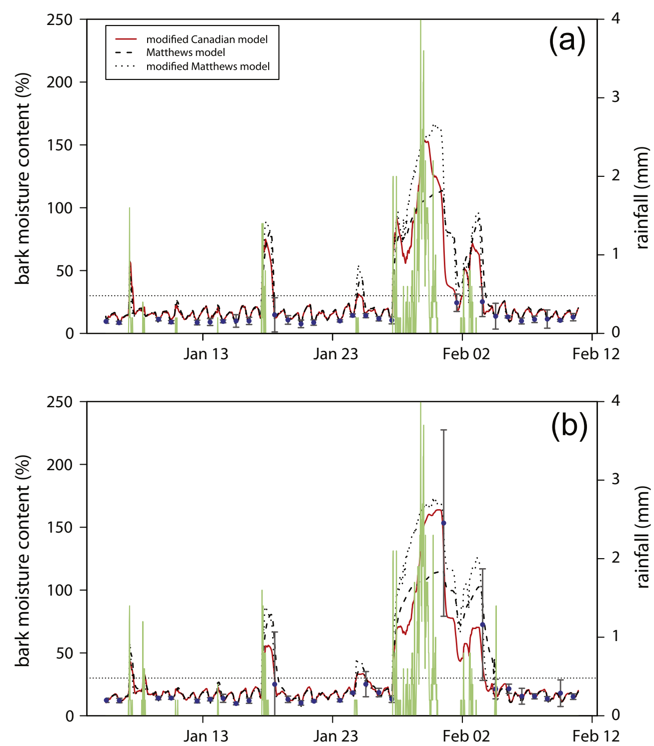

Fig. 3. Time series of the mean FMC for bark (blue dots) for (a) dry site, (b) damp site. The horizontal dotted line indicates 30% moisture content. 95% confidence intervals for the true FMC values are shown as grey vertical lines with end bars. The modified Canadian model (red), the Matthews model (black dashed) and the modified Matthews model (black dotted) are overlaid. Rainfall is shown in green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Minimum, median and maximum moisture contents of the fuel components on each site.

	Min	Median	Max
Dry site			
Bark	7.6	10.4	25.2
Top litter	6.7	9.5	62.5
Profile	6.3	13.1	149.0
Damp site			
Near-surface	8.7	13.7	83.0
Bark	9.7	14.0	153.3
Top litter	7.2	16.3	147.1
Profile	10.7	33.7	176.1

Table 2
Parameters for the modified Canadian model (Eqs. (6) and (8)): minimised values, and means and standard deviations of bootstrap samples. Equivalent response times are given for α.

	α	Response time (hrs)	Mean (α)	sd (α)	β	Mean (β)	sd (β)
Near surface	0.39	0.85			21.41		
Bark	0.1827	1.8	0.1827	0.03070	7.463	10.000	8.782
Top litter	0.08155	4.0	0.08343	0.01792	21.41	24.205	13.703
Profile	0.04493	7.4	0.04685	0.01634	27.05	45.426	32.459

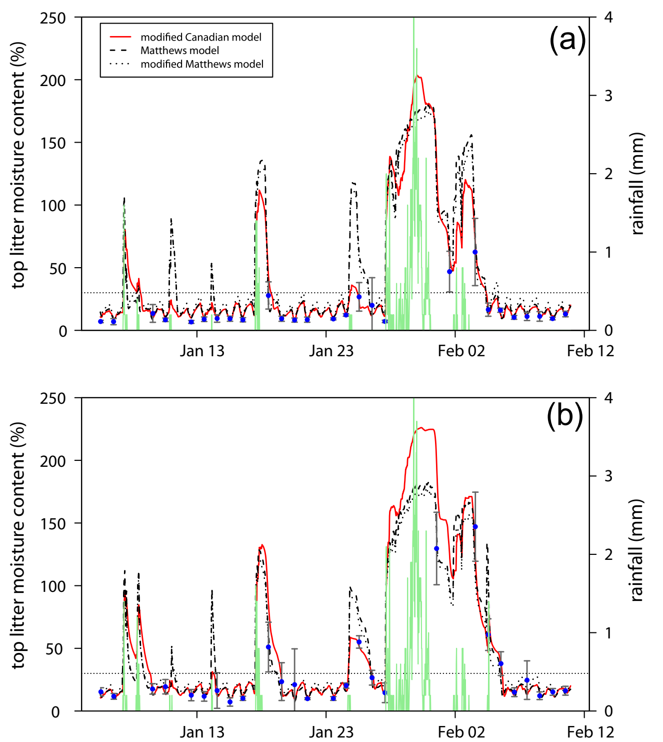

Fig. 4. Time series of the mean FMC for top litter (blue dots) for (a) dry site, (b) damp site. The horizontal dotted line indicates 30% moisture content. 95% confidence intervals for the true FMC values are shown as grey vertical lines with end bars. The modified Canadian model (red), the Matthews model (black dashed) and the modified Matthews model (black dotted) are overlaid. Rainfall is shown in green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

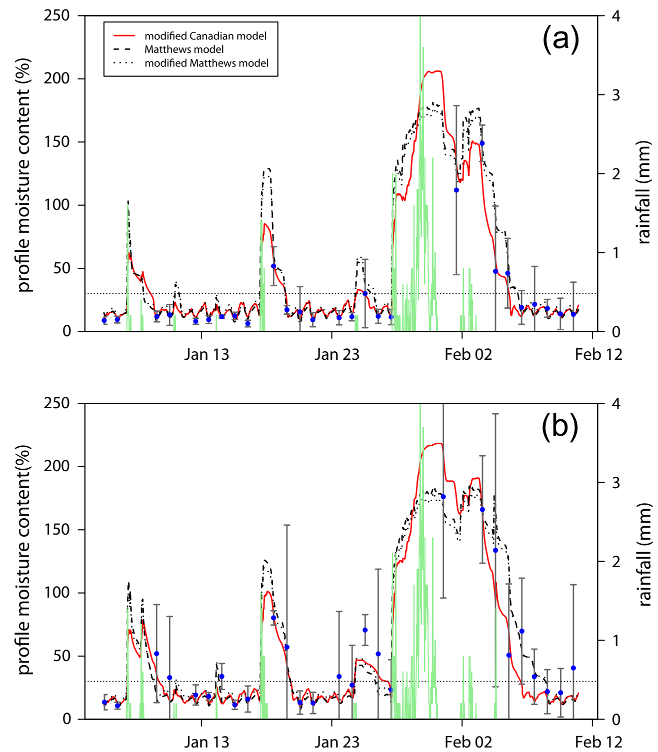

Fig. 5. Time series of the mean FMC for profile litter (blue dots) for (a) dry site, (b) damp site. The horizontal dotted line indicates 30% moisture content. 95% confidence intervals for the true FMC values are shown as grey vertical lines with end bars. The modified Canadian model (red), the Matthews model (black dashed) and the modified Matthews model (black dotted) are overlaid. Rainfall is shown in green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

both unmodified and modified Matthews models are shown in Fig. 2 (near-surface), Fig. 3a, b (bark:dry,damp), Fig. 4a, b (top litter:dry,damp) and Fig. 5b (profile:dry,damp). The error statistics are given in Table 3.

The modified Matthews model was an improvement on the original model as would be expected. There was little difference in the performance between the modified Matthews model and the modified Canadian model on the dry site. Overall the modified Matthews model performed better than the modified Canadian model on the damp site, particularly for the bark and the near-surface fuels. The predictions were generally poorer on the damp site, particularly for the surface and profile litter. However, both models seem to be responding correctly to wetting and drying.

The number of observations for the three models which fell into the categories GB (good burn), PB (patchy burn), WTO (wasted time over-prediction), WTU (wasted time under-prediction) and MO (missed opportunity) are shown in Table 4, and displayed graphically in Fig. 6 in the range of predicted and observed values less than 30%. The modified Canadian model was the best predictor of good burning conditions predicting correctly for 11 days put of a possible 13, compared to the 7 and 8 for the unmodified and modified versions of the Matthews model which tended to over-predict on the dry site for lower moisture contents. Using the modified Canadian model would have resulted in slightly more patchy burns than using the Matthews models, but would have resulted in less missed opportunities. Using the modified Matthews model would have resulted in 13 days of wasted time compared to 7 for the unmodified model and the modified Canadian model. This was caused by overpredictions on the dry site and underpredictions on the damp site.

4. Discussion

The modified Canadian model and the modified Mathews model both produced reasonable fits to the data (Table 3). The modified Matthews model was superior on the damp sites, but at the expense of predicting good burning conditions when the conditions were either too dry or too wet. For use in prescribed burning the modified Canadian model was the better predictor of good burning conditions, and resulted in the least missed opportunities and wasted time (Table 4).

Table 3
RMSE, MAE and MBE values for model predictions of fuel moisture. Positive values of MBE indicate under-prediction.

Site	Strata	Modified Canadian			Matthews			Modified Matthews		
		RMSE	MAE	MBE	RMSE	MAE	MBE	RMSE	MAE	MBE
Dry	Bark	1.7	1.3	−0.9	9.9	3.9	−3.3	1.4	1.2	0.0
	Top Litter	5.0	3.2	−1.7	8.9	4.7	−2.6	6.8	4.2	−2.5
	profile	8.2	4.9	0.6	10.7	6.0	−2.2	9.6	5.8	−2.2
Damp	Near surface	14.6	6.4	0.8	12.8	6.4	−1.5	9.0	4.5	−0.3
	Bark	8.3	4.0	2.8	11.0	5.4	−0.1	3.1	2.1	2.0
	Top litter	16.1	7.9	-0.9	13.9	8.3	0.5	12.0	6.8	0.4
	Profile	18.1	13.8	9.6	21.6	14.7	5.3	19.6	13.0	4.4

Table 4
GB (good burn), PB (patchy burn), WTO (wasted time: under-prediction), WTU (wasted time: over-prediction) and MO (missed opportunity) counts for model predictions of top litter fuel moisture. Maximum possible GB days shown in parentheses.

Site	*n*	Modified Canadian					Matthews					Modified Matthews				
		GB	PB	WTO	WTU	MO	GB	PB	WTO	WTU	MO	GB	PB	WTO	WTU	MO
Dry	27	4(5)	3	3	0	1	3	3	4	0	2	3	3	7	0	2
Damp	27	7(8)	4	3	1	1	4	2	0	3	4	5	2	2	4	3
Total	54	11(13)	7	6	1	2	7	5	4	3	6	8	5	9	4	5

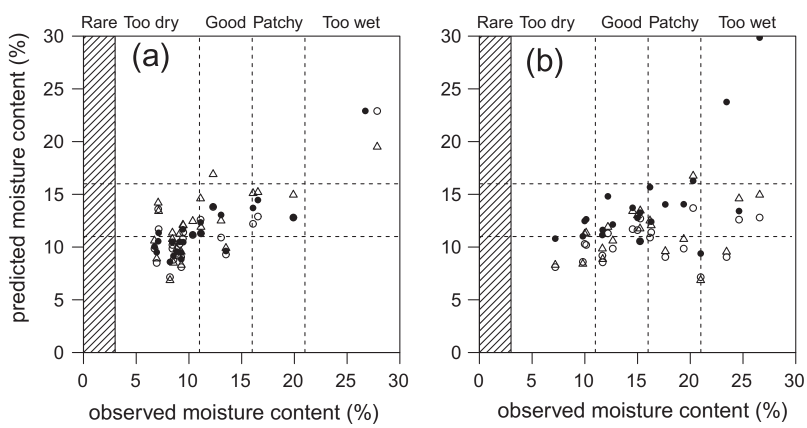

Fig. 6. Predicted versus observed values for top litter moisture (only values 30% or less are shown) for (a) dry site, (b) damp site. Regions are indicated with respect to decisions and consequences. Filled circles represent modified Canadian model; empty circles represent Matthews model and empty triangles represent modified Matthews model.

Parameters for both the modified Canadian model and the modified Mathews model were obtained from the data and thus it is not surprising that the models predict well. Using the models to make predictions for an independent data set would provide a more robust evaluation. Unfortunately days with radiation data and sufficient rainfall to test the model were few. The models will be tested further in a future paper which includes the use of modelled radiation and extra sites.

The parameters of the modified Canadian model were fuel-layer specific (Table 2). From physical principles Wotton (2009) fixed β to be 100 in Eq. (7) but this does not allow for bark run-off and seepage from the top litter into the lower layers, and from the profile layers into the soil. The formulation in Eq. (8) allow for a run-off effect. The estimated values of β are less for bark than for top litter and profile, and it seems reasonable that run off is greater for bark than for litter and profile. The standard errors for β are however, very large. These large standard errors partly reflect the lack of data after a rain event, and partly the variability of the observed moisture content. The parameters for the near-surface fuel were poorly determined, and need verification.

The FFMC model for pine needles has a response time of 5.72 h at standard conditions. The grassland model given in Wotton (2009) has a response time of 0.85 h under these conditions. For the models described here, under drying conditions after rain, the response times for the profile, top litter, bark and near-surface are 7.4 h, 4 h, 1.8 h, and 0.85 h, respectively (Table 2). These seem quite reasonable. Verification data is needed to test this model before it could be used in practice, particularly given the high uncertainty in parameters for the modified Canadian model and dependence on relatively few rainy observations.

The two models responded differently to rainfall (Figs. 2–5). The modified Canadian model tends to reach higher maximum values during rainfall and dried more rapidly than the Matthews model. This difference was most pronounced for profile fuels (Fig. 5) and least for bark (Fig. 3). There is not sufficient data to determine which behaviour more correctly represents the response of the fuels given that only a small number of the observations were rain-affected and these values had the largest sample variance.

Parameter fitting for the Matthews model increased the amount of wetting and rate of drying for bark fuels (Fig. 3). Significant changes in parameters and prediction error were expected because the initial parameters were developed for suspended fuels rather than stringy bark. Changes for top litter (Fig. 4) and profile (Fig. 5) were smaller and resulted in a reduction in wetting for both layers.

This was consistent with the findings of Matthews (2006) and Matthews et al. (2007) where fuel wetting was also over-predicted using the initial parameter set but improved by reducing retention of surface water. Given the high sample variation in the few rain-affected samples which determined the parameter fit it is not clear that this fitting makes a significant practical difference to the Matthews model, the improvement in error statistics in Table 3 notwithstanding. Furthermore the statistics for the prediction of prescribed burning conditions are worse with the unmodified model.

Within the 'wasted time' category there were two modes of model failure, under and over prediction (Fig. 1). Under predictions are definitely wasted time because if afternoon (i.e. minimum) FMC is above 22% the fuel will not be dry until the following day. For over predictions the model has correctly predicted that the fuels are dry enough to be driven by EMC but has a problem with the shape of its EMC curves or response to solar heating. Since FMC increases in the late afternoon there may be a chance to complete a planned burn later in the day. On the other hand for a large burn requiring a full day to complete this would still be a wasted day. The analysis performed here has only considered the ability of the models to correctly reproduce FMC measurements in each category and not the length of burning windows. Consideration of the ability of the models to predict the length of burning conditions would be a useful addition but would require additional measurements or use of extant fire behaviour records which is beyond the scope of this study.

5. Management implications

The combination of improved fuel moisture models and more localised forecasts would significantly improve agencies' abilities to:

- more accurately predict when and where opportunities for conducting burns will occur,
- conduct safer planned burning operations,
- be more aware of when they could expect some post-burn control difficulties,
- more accurately predict spread of fires and therefore provide better information to communities,
- improve prepositioning of suppression and prescribed burning resources (Higgins et al., 2011).

In this study, it was possible to distinguish FMC between the sites without needing to fit parameters for each site. This suggests that local meteorology is more important than fuel-specific parameters for the differences between dry and damp forest although this may not be true for sites with very deep litter layers. This result is encouraging especially when coupled with the introduction of the Graphical Forecast Editor (GFE) (Anon, 2012) that has enabled land and fire management agencies to receive much improved localised weather forecasts on 3 by 3 km grids, although corrections for the effect of canopy structure on micrometeorology will still be needed in areas of complex topography. This change has allowed land managers to identify the possible 'windows of opportunity' for burning up to seven days in advance and enables better resource planning for the forthcoming period. It also provides guidance to land managers where to conduct more specific weather measurements by using Automatic Weather Stations (AWS) and fuel moisture measurements by using devices such as Wiltronics (Chatto and Tolhurst, 1997). Those more specific measurements further enhance the decision making.

If resources are deployed when models are predicting optimal burning conditions but the observed fuel moisture is between 9% and 13% in lighter fuels or between 11% and 13% in heavier fuels, land managers have an option to wait for the relative humidity to start increasing and ignite once the fuel moisture starts increasing. These conditions normally occur later in the day and throughout the night. In this case they will incur some additional costs potentially for overtime rather than this being an unproductive day.

This study has considered only one aspect of prescribed burning, fuel moisture content. In reality decisions about burning also require consideration of fuels, topography, winds and conditions on subsequent days (Marsden-Smedley, 2009). Thus, our results should not be considered a prescribed burn decision making tool in their own right. Rather, we have shown that the models studied can usefully provide site-specific information about fuel moisture content within a decision making system.

6. Conclusions

Both modelling approaches provided good predictions that could be used operationally. It was encouraging to see that it is possible to get as similar a result from the very simple Canadian model as from the full process model. However for operational use, the model would need to be validated using independent data and possibly recalibrated in different vegetation types. The Matthews model was greatly improved by calibration to the specific vegetation further indicating that calibration would also be recommended for use in different vegetation types. However this calibration was at the expense of predictions for dry conditions, so the unmodified Matthews model was superior for use in prescribed burning.

The data used in this paper were sampled from flat ridge tops thus giving an incomplete picture of the fuel moisture variations across the lanscape. The effect of variation of fuel moisture with aspect will be investigated in a further paper.

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References

Alexander, M.E., Lee, B.S., Lee, C.Y., 1984. Hourly calculation of the Fine Fuel Moisture Code, Initial Spread Index, and Fire Weather Index with the Texas Instruments Model 59 hand-held calculator. Report File Report NOR-5-191. Canadian Forestry Service, Northern Forestry Research Centre, Edmonton, Alberta.

Anderson, S.A.J., Anderson, W.R., 2009. Predicting the elevated dead fine fuel moisture content in gorse (*Ulex eurapaeus* L.) shrub fuels. Can. J. Forest Res. 39, 2355–2368. http://dx.doi.org/10.1139/X09-142.

Anon, 2012. Next Generation Forecast and Warning System. Australian Government Bureau of Meteorology, Melbourne.

Berry, S.L., Roderick, M., 2005. Plant–water relations and the fibre saturation point. New Phytol. 168, 25–37.

Byram, G.M., Jemison, G.M., 1943. Solar radiation and forest fuel moisture. J. Agric. Res. 67, 149–176.

Catchpole, E.A., Catchpole, W.R., Viney, N.R., McCaw, W.L., Marsden-Smedley, J.B., 2001. Estimating fuel response time and predicting fuel moisture content from field data. Int. J. Wildland Fire 10, 215–222. http://dx.doi.org/10.1071/WF01011.

Chatto, K., Tolhurst, K., 1997. The development and testing of the Wiltronics T-H fine fuel moisture meter. Research report 46. Fire management branch.

Cruz, M.G., Matthews, S., Gould, J., Ellis, P., Henderson, M., Knight, I., Watters, J., 2010. Fire dynamics in mallee-heath: Fuel, weather and fire behaviour prediction in South Australian semi-arid shrublands. Rep. A.10.01. Bushfire CRC, East Melbourne, Australia.

Duncan, F., Brown, M.J., 1985. Dry sclerophyll vegetation in Tasmania: extent and conservation status of the communities. Wildlife Division Tech. Rep. 85/1. National Parks and Wildlife Service, Tasmania, Australia.
Efron, B., Tibshirani, R., 1993. An Introduction to the Bootstrap. Chapman and Hall, New York.
Gould, J.S., McCaw, W.L., Cheney, N.P., 2011. Quantifying fine fuel dynamics and structure in dry eucalypt forest (*Eucalyptus marginata*) in Western Australia for fire management. For. Ecol. Manage. 232, 531–546.
Higgins, A., Whitten, S., Slijepcevic, A., Fogarty, L.G., Laredo, L., 2011. An optimisation modelling approach to seasonal resource allocation for planned burning. Int. J. Wildland Fire 20, 175–183. http://dx.doi.org/10.1071/WF09103.
Hines, F., Tolhurst, K.G., Wilson, A.A.G., McCarthy, G.J., 2010. Overall fuel hazard assessment guide. report 82. Department of Sustainability and Environment, Melbourne, Australia.
Hollander, M., Wolfe, D.A., 1999. Nonparametric Statistical Methods, second ed. John Wiley & Sons, New York.
Johnson, D.J., 1994. Mapping the vegetation of Hobart. M.Env.St thesis, Centre for Environmental Studies, Department of Geography and Environmental Studies, University of Tasmania, Australia.
Kirkpatrick, J.B., Peacock, R.J., Cullen, P.J., Neyland, M.G., 1988. The Wet Eucalypt Forests of Tasmania. Tasmanian Conservation Trust, Hobart, Tasmania, Australia.
Lawson, B.D., Armitage, O.B., Hoskins, W.D., 1996. Diurnal variation in the Fine Fuel Moisture Code: tables and computer source code. Canada-British Columbia Partnership Agreement on Forest Resource Development FRDA Report No. 245. Canadian Forest Service and BC Ministry of Forests, Victoria, BC.
Makridakis, S., Wheelwright, S.C., Hyndman, R.J., 1998. Forecasting, Methods and Applications. Wiley.
Marsden-Smedley, J.B., 2009. Planned Burning in Tasmania: Operational Guidelines and Review of Current Knowledge. Report for Tasmanian Fire Research Fund.
Marsden-Smedley, J.B., Anderson, W.R., 2011. Fuel Load and Fuel Hazard Prediction in Tasmanian Dry Forests. Report for Tasmanian Fire Research Fund.
Matthews, S., 2006. A process-based model of fine fuel moisture. Int. J. Wildland Fire 15, 155–168. http://dx.doi.org/10.1071/WF05063.
Matthews, S., 2010. Effect of drying temperature on fuel moisture content measurements. Int. J. Wildland Fire 19, 800–802.
Matthews, S., 2013. Dead fuel moisture research: 1991-2012. Int. J. Wildland Fire 23, 78–92. http://dx.doi.org/10.1071/WF13005.
Matthews, S., McCaw, W.L., 2006. A next-generation fuel moisture model for fire behaviour prediction. For. Ecol. Manage. 234 (Supplement, S91). http://dx.doi.org/10.1016/j.foreco.2006.08.127.
Matthews, S., McCaw, W.L., Neal, J., Smith, R., 2007. Testing a process-based fine fuel moisture model in two forest types. Can. J. Forest Res., 37. http://dx.doi.org/10.1139/x06-207.
McCaw, W.L., Gould, S.J., Cheney, N.P., Ellis, P.F.M., Anderson, W.R., 2012. Changes in behaviour of fire in dry eucalypt forest as fuel increases with age. For. Ecol. Manage. 271, 170–181. http://dx.doi.org/10.1016/j.foreco.2012.02.003.
Merrill, D.F., Alexander, M.E. (Eds.), 1987. Glossary of Forest Fire Management Terms. National Research Council of Canada, Canadian Committee on Forest Fire Management, Ottawa, Ontario, Canada.
Nelson, R.M., 1984. A method for describing equilibrium moisture content of forest fuels. Can. J. For. Res. 14, 597–600. http://dx.doi.org/10.1139/x84-108.
R Core Team, 2014. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
Slijepcevic, A., Anderson, W.R., Matthews, S., 2013. Testing existing models for predicting hourly variation in fine fuel moisture in eucalypt forests. For. Ecol. Manage. 306, 202–215. http://dx.doi.org/10.1016/j.foreco.2013.06.033.
Sneeuwjagt, R., Peet, G.B., 1985. Forest fire behaviour tables for Western Australia.
Tolhurst, K.G., Cheney, N.P., 1999. Synopsis of the Knowledge Used in Prescribed Burning. Department of Natural Resources and Environment, VIC, Australia.
Van Wagner, C.E., 1977. A Method of Computing Fire Fuel Moisture Code Throughout the Diurnal Cycle Information Report PS-X-69. Canadian Forest Service, Chalk River, Ontario, Canada.
Van Wagner, C.E., 1987. Development and Structure of the Canadian Forest Fire Weather Index System Technical Report 35. Canadian Forest Service, Chalk River, Ontario, Canada.
Van Wagner, C.E., Pickett, T.L., 1985. Equations and FORTRAN program for the Canadian Forest Fire Weather Index System. Forestry Technical Report 33. Canadian Forestry Service, Government of Canada, Ottawa, ON.
Viney, N.R., 1991. A review of fine fuel moisture modelling. Int. J. Wildland Fire 1, 215–234. http://dx.doi.org/10.1071/WF9910215.
Willmott, C.J., 1982. Some comments on the evaluation of model performance. Bull. Am. Meteor. Soc. 63, 1309–1313.
Wotton, B.M., 2009. A grass moisture model for the Canadian Forest Fire danger Rating System. In: 8th Fire and Forest Meteorology Symposium, Kalispell, MT, USA.