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Article *in* International Journal of Wildland Fire · January 2006

DOI: 10.1071/WF05063

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www.publish.csiro.au/journals/ijwf *International Journal of Wildland Fire*, 2006, **15**, 155–168

A process-based model of fine fuel moisture

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Abstract. This paper presents the first complete process-based model for fuel moisture in the litter layer. The model predicts fuel moisture by modelling the energy and water budgets of the litter, intercepted precipitation, and air spaces in the litter. The model was tested against measurements of fuel moisture from two sets of field observations, one made in Eucalyptus mallee-heath under dry conditions and the other during a rainy period in *Eucalyptus obliqua* forest. The model correctly predicted minimum and maximum fuel moisture content and the timing of minima and maxima in the mallee-heath. Under wet conditions, wetting and drying of the litter profile were correctly predicted but wetting of the surface litter was over-predicted. The structure of the model and the dependence of predictions on model parameters were examined using sensitivity and parameter estimation studies. The results indicated that it should be possible to adapt the model to any forest type by specifying a limited number of parameters. A need for further experimental research on the wetting of litter during rain was also identified.

Introduction

The moisture content of fine fuels (FMC) is an important variable determining fire ignition and behaviour. Because field measurement of FMC is labour intensive, and because of the need to predict FMC for planning prescribed burning and wildfire suppression operations, models have been developed to predict fuel moisture from weather observations or forecasts.

FMC models currently in use around the world are of two types of empirical models. The first predicts FMC as a function of weather variables, e.g. the model incorporated in the McArthur (1967) Forest Fire Danger Meter (FFDM). The second predicts changes in FMC as a function of weather conditions, e.g. the model included in the Forest Fire Behaviour Tables (Sneeuwjagt and Peet 1998) and the Fine Fuel Moisture Code (van Wagner 1987). These models relate FMC or changes in FMC to weather conditions using functions derived from field observations by using statistical methods. Empirical models do not attempt to directly represent the physical processes that determine fuel moisture. Although this approach to predicting FMC has produced useful models, empirical models have several important limitations. Empirical models cannot easily be adapted for use in new locations where the relationships between weather and fuel moisture differ. Improvements in understanding of the physical processes that determine fuel moisture cannot be incorporated into the model, nor can variables not included in the original model but later shown to affect fuel moisture be included, e.g. solar radiation.

An alternative method for predicting FMC that avoids these difficulties is to use a process-based model. A process-based model explicitly represents the physical processes that determine FMC. This type of model can be adapted for different forest types and locations by changing model parameters, and model processes can be improved as new knowledge becomes available. In addition, new processes can be introduced to the model, and fuel types can be included that were not previously considered important for predicting fire behaviour, e.g. near-surface fuels.

Fosberg (1975) presented an early attempt at process-based modelling of forest litter. Transfers of water vapour and heat in the litter layer air spaces were modelled using diffusion equations. The response of litter temperature and moisture content to changes in air temperature and humidity were represented using exponential decay equations. The model was run by specifying temperature and humidity at the top of the litter layer and solving the equations as a function of time at several depths within the litter. Because the model did not include radiation or rainfall, it was unsuitable for use in the field. One important insight from the model runs presented by Fosberg (1975) was that the rate of response of FMC to changing weather conditions was determined largely by the response of the litter solids, rather than by diffusion through the airspaces. Using this observation, Nelson (1991) developed a model assuming FMC followed an exponential decay curve towards an equilibrium moisture content, which was a function of fuel temperature and relative humidity. Solar heating of the fuel was included using the semi-physical model

 10.1071/WF05063 1049-8001/06/020155

of Byram and Jemison (1943). The model performed well in dry conditions but owing to lack of any treatment of rainfall is unsuitable in wet conditions.

Forest hydrology models that include a litter layer and respond to rainfall have been developed by Ogee and Brunet (2002) and Paul *et al.* (2003). Litter moisture was represented in both models as a single value, which was increased by rainfall and decreased by drainage and evaporation. Although soil moisture predictions in both models were sensitive to the presence or absence of litter, the predictions of litter moisture content were not validated. Because these models do not allow resolution of the response of litter moisture to relative humidity or vertical variation in moisture content, neither is suitable for bushfire applications.

To overcome the limitations of previous models, we have developed a process-based model that treats fuel moisture, intercepted rainfall, and humidity in the litter air spaces separately. The present paper describes the model and compares model predictions with two sets of field observations. A sensitivity study is presented to examine the dependence of the model on its parameters. The potential to improve model performance by more accurately measuring parameters is examined by attempting to fit the model to field observations.

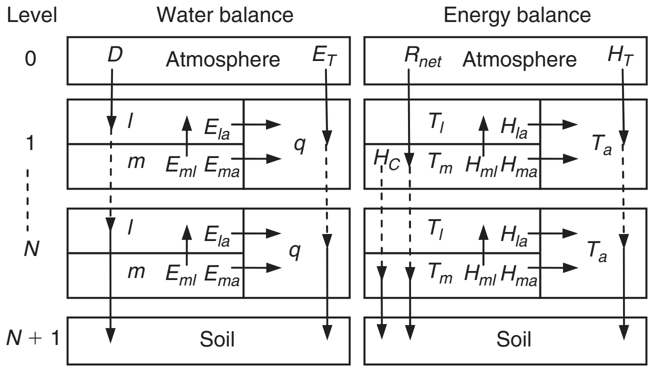

Fig. 1. Model structure: the model predicts the energy and water balance of the litter at N nodes between the soil and atmosphere. Each node is divided into three materials: litter, free water, and litter air spaces. The water content of each material is represented as m, l, and q, respectively, in the water balance. The temperatures of the materials are T_m, T_l, and T_a, respectively. Fluxes between materials are indicated by arrows with fluxes positive in the direction of the arrow. See the text for an explanation of fluxes.

Model description

The model represents transfers of energy and water in a litter bed containing 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 N equally spaced nodes within the litter bed, thus requiring budget equations for six quantities:

- T_m, litter temperature (K),
- T_l, the temperature of free liquid water on the litter surfaces (K),
- T_a, air temperature (K),
- m, litter moisture content (kg water per kg of dry litter),
- l, amount of liquid water (kg of water per m^3 of litter layer),
- q, specific humidity (kg of water vapour per kg of air).

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 and between levels within a given material (Fig. 1).

Radiation

Radiation fluxes between model nodes are calculated using a simplification of the procedure described by Novak *et al.* (2000). That model assumes that the litter elements are opaque to both short- and longwave radiation and that the longwave emissivity is equal to 1. Shortwave radiation is not separated into direct and diffuse components and forward scattering is assumed to be negligible. Secondary shortwave reflections have not been included in our adaptation of the model.

The litter layer is characterised by the shortwave reflectance, α_l, of the litter elements and by a transmittance function, τ

$$\tau_i = e^{-\gamma \Lambda i}, \tag{1}$$

where τ_i is the fraction of radiation transmitted through i model layers, Λ is the one-sided leaf area index of one layer, and γ is an attenuation parameter. Following Novak *et al.* (2000), the downwelling shortwave irradiance below the ith layer is

$$S_{dn,i} = S_0 \tau_i, \quad 0 \le i < N, \tag{2}$$

where S_0 (W m^{-2}) is the solar irradiance above the litter layer. Upwelling shortwave irradiance is

$$S_{up,i} = \alpha_s S_{dn,N} \tau_{N-i} + \sum_{j=i}^{N-1} \alpha_l (S_{dn,j} - S_{dn,j+1}) \tau_{j-i}, \quad 0 \le i < N-1, \tag{3}$$

where $S_{up,N} = \alpha_s S_{dn,N}$ where α_s is the shortwave reflectance of the soil.

Downwelling longwave irradiance below the ith layer is

$$L_{dn,i} = F_{0,i} L_0 + \sum_{j=1}^{i} F_{j,i} \sigma T_j^4, \quad 1 \le i \le N, \tag{4}$$

$$F_{j,i} = \tau_{i-j} - \tau_{i-j+1}, \quad 1 \le j \le i, \tag{5}$$

$$F_{j,i} = \tau_{j-i-1} - \tau_{j-i}, \quad i < j < N+1, \tag{6}$$

where L_0 is the downwelling irradiance at the top of the litter layer, $F_{0,i} = \tau_i$, and $F_{N+1,i} = \tau_{N-i}$. Upwelling longwave irradiance below the ith layer is

$$L_{up,i} = F_{N+1,i}\sigma T_s^4 + \sum_{j=i+1}^{N} F_{j,i}\sigma T_j^4, \quad 0 \le i < N, \tag{7}$$

where $L_{up,N} = \sigma T_s^4$, T_s is soil temperature (K), and F is given by Eqns (5) and (6). Net radiation is the sum of the four components

$$R_{net,i} = S_{dn,i} - S_{up,i} + L_{dn,i} - L_{up,i} \tag{8}$$

Vertical transport of heat and water

Transport of heat and water vapour through the air spaces of the litter layer is represented using the flux-gradient relationship for heat, H_T, and water vapour, E_T, fluxes

$$H_T = \rho_{air} C_p D_T \frac{\partial T_a}{\partial z}, \tag{9}$$

$$E_T = \rho_{air} D_T \frac{\partial q}{\partial z}, \tag{10}$$

where z is height above the soil surface (m), ρ_{air} is air density ($1.2\,\mathrm{kg\,m^{-3}}$), C_p is the specific heat of dry air ($1004.5\,\mathrm{J\,kg^{-1}\,K^{-1}}$), and D_T is turbulent diffusivity ($\mathrm{m^2\,s^{-1}}$). D_T is modelled as a function of depth

$$D_T(z) = D_{T0} e^{\chi(z/h-1)}, \tag{11}$$

where h is litter layer depth (m), and D_{T0} and χ are empirical functions of wind speed.

Conduction

Conduction of heat due to vertical gradients in litter temperature, H_C, is represented using Fourier's law as

$$H_C = K_C \frac{\partial T_m}{\partial z}, \tag{12}$$

where K_C is the conductance ($\mathrm{W\,m^{-1}\,K^{-1}}$). A separate heat flux representing conductance through intercepted precipitation on the surface of the litter has not been included. Heat transfer between the litter and intercepted precipitation is represented as a conductive flux, H_{ml}

$$H_{ml} = K_{ml,H}(T_m - T_l), \tag{13}$$

where $K_{ml,H}$ is the conductance ($\mathrm{W\,m^{-2}\,K^{-1}}$).

Drainage

Interception of rainfall and drainage through the litter is represented by generalising the principles of the single layer model of Rutter *et al.* (1971) to apply in a multilayer model. The key assumptions of the present model are:

- Each layer intercepts some fraction, D_p, of the water flux from above,
- Each layer has a storage capacity, D_s ($\mathrm{kg\,kg^{-1}}$),
- Once the storage capacity is exceeded, water drains through to the next layer with the drainage rate proportional to the square of the excess water.

The drainage flux from the ith layer is then formulated recursively as

$$D_i = D_p D_{i-1} + D_a(\max\{0, l_i - \rho_{bulk} D_s\})^2, \quad 1 \le i \le N, \tag{14}$$

where D_0 is the rainfall rate ($\mathrm{kg\,m^{-2}\,s^{-1}}$, proportional to $\mathrm{mm\,s^{-1}}$), D_a is the drainage coefficient ($\mathrm{kg^{-1}\,m^4\,s^{-1}}$), and D_p is equal to τ_1 (Eqn 1). D_p is set equal to τ_1 on the assumption that the physical barrier of the litter blocks raindrops falling in a straight line in the same proportion as radiation. The dependence of drainage flux, D_i on storage, l_i has been modified from the exponential form used by Rutter *et al.* (1971) to a quadratic term to reduce the number of parameters required from two to one. This modification was required to allow estimation of the drainage parameter from measurements of the difference between D_s and l (see below).

Litter vapour exchange

The water vapour flux between the litter and air, E_{ma}, is represented in terms of the fuel relative humidity and a surface conductance

$$E_{ma} = \rho_{air} K_{ma,E}(RH \cdot q_{sat} - q), \tag{15}$$

where $K_{ma,E}$ ($\mathrm{m\,s^{-1}}$) is the litter surface conductance, RH is the fuel relative humidity, q_{sat} is saturation specific humidity ($\mathrm{kg\,kg^{-1}}$) at litter temperature, and q is specific humidity in the litter layer air spaces ($\mathrm{kg\,kg^{-1}}$). Fuel relative humidity is represented as a function of fuel moisture content and temperature by inverting the two-parameter model of Nelson (1984) for equilibrium moisture content

$$RH = \exp\left(\frac{-4.19M}{RT_m}\exp(mB + A)\right), \tag{16}$$

where M is the molecular mass of water ($18.0153\,\mathrm{g\,mol^{-1}}$), R is the universal gas constant ($8.314\,\mathrm{J\,mol^{-1}\,K^{-1}}$), A and B are empirical parameters.

In fuel moisture modelling studies, vapour exchange has usually been represented using an equilibrium moisture content, m_e, curve, a function of relative humidity and temperature, and a response time, with the assumption that m follows an exponential decay curve towards m_e. The use of an exponential decay curve with a response time was initially derived by Byram (1963) from a diffusion equation. Byram noted that because diffusivity depends on temperature, so too should response time, as has been observed in the laboratory by van Wagner (1979). van Wagner (1979) also observed

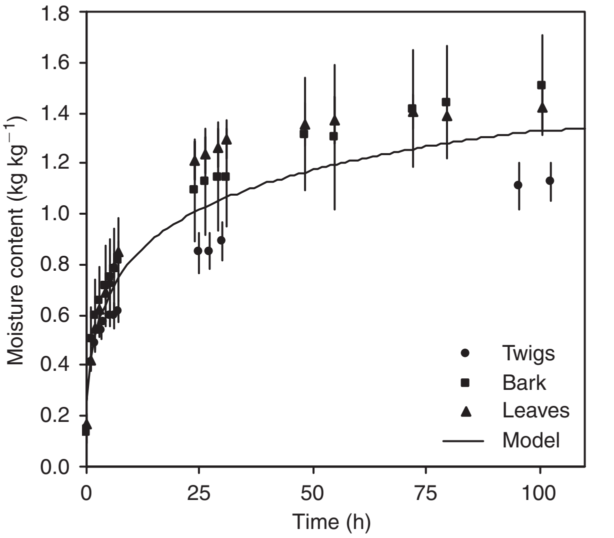

Fig. 2. Absorption of water by *Eucalyptus obliqua* litter. The moisture content of three samples each of leaves, bark, and twigs immersed in water were measured for 100 h by periodically weighing the samples after removing them from the water and removing surface water. Vertical bars are one standard deviation. The model is a weighted least-squares fit to Eqn (17), using weights of 0.5, 0.1, and 0.4 for leaves, bark, and twigs, respectively. Note that in Eqn (17), time is measured in seconds.

that the response time decreased as temperature increased. However, for ease of computation, earlier models have often included a constant response time (e.g. Nelson 1991). The constant response time most commonly used in prior studies may be related to $K_{ma,E}$ by fitting drying curves from an exponential decay model to a numerical solution to Eqn (37). For example, a 1 h response time at 20°C corresponds to $K_{ma,E} = 0.0006\,\mathrm{m\,s^{-1}}$.

Litter liquid water absorption

Liquid water on the surfaces of the litter elements is absorbed until the litter reaches saturation. For large diameter fuel, it is necessary to model capillary flow within the particles (Nelson 2000), but for fine litter it is possible to simply specify a flux across the surface of the fuel based on laboratory observations (Fig. 2). The increase with time of m can be represented by

$$m(t) = L_b + L_a \ln(t), \tag{17}$$

where L_a and L_b are empirical parameters. Eqn (17) can be differentiated to give

$$\frac{\partial m}{\partial t} = \frac{L_a}{t}, \tag{18}$$

and Eqn (18) then substituted back into Eqn (17), resulting in

$$\frac{\partial m}{\partial t} = L_a \exp\left(\frac{L_b - m}{L_a}\right). \tag{19}$$

For convenience in later calculations, the change in m is rewritten as the product of a flux and surface area-to-volume ratio

$$\rho_{litter} \frac{\partial m}{\partial t} = -\mu E_{ml}, \tag{20}$$

$$E_{ml} = \frac{-\rho_{litter}}{\mu} L_a \exp\left(\frac{L_b - m}{L_a}\right), \tag{21}$$

where μ is the surface area-to-volume ratio of the litter. As the litter eventually approaches a saturation moisture content, m_{sat}, but Eqn (17) is unbounded above as $m \to \infty$, the condition $E_{ml} = 0$ is imposed when m reaches m_{sat}.

Litter boundary layer fluxes

The boundary layer heat fluxes between the litter solids and air spaces, H_{ma}, and between surface water and air spaces, H_{la}, are given by

$$H_{ma} = \rho_{air} C_p K_{ma,H} (T_m - T_a), \tag{22}$$

$$H_{la} = \rho_{air} C_p K_{la,H} (T_l - T_a), \tag{23}$$

where $K_{ma,H}$ and $K_{la,H}$ are conductances ($\mathrm{m\,s^{-1}}$), calculated on the assumption that the litter elements can be treated as flat plates, giving (Monteith 1975)

$$K_{ma,H} = K_{la,H} = \begin{cases} 3.23 \cdot 10^{-3} \left(\frac{U}{d}\right)^{0.5}; & \frac{d(T_l - T_a)}{U^2} < 474 \\ 1.15 \cdot 10^{-3} \left(\frac{T_l - T_a}{d}\right)^{0.25}; & \frac{d(T_l - T_a)}{U^2} \geq 474 \end{cases}, \tag{24}$$

where U is wind speed ($\mathrm{m\,s^{-1}}$) and d is the width of the plate (m). The top term represents forced convection and the bottom represents free convection. Wind speed is calculated by attenuating the wind speed at 10 cm above the litter layer using the diffusivity attenuation function of Eqn (11). The boundary layer evaporation flux from intercepted rainfall to air spaces is

$$E_{la} = \rho_{air} K_{la,E} (q_{sat} - q), \tag{25}$$

where conductance $K_{la,E}$ ($\mathrm{m\,s^{-1}}$) is (Monteith 1975)

$$K_{la,E} = \left(\frac{\kappa_h}{\kappa_v}\right)^{0.67} \quad K_{la,H} = 0.9 K_{la,H}, \tag{26}$$

where κ_h is the thermal diffusivity of dry air and κ_v is the diffusion coefficient for water vapour in air. E_{la} is set to zero if there is no water present.

Model equations

The model uses budget equations for the energy and water content of litter, free water, and air. The fluxes across material interfaces described above are converted to rates of change in energy or water content by multiplying by the appropriate surface area-to-volume ratio

$$\mu_{x,y} = \frac{SA_{xy}}{V_x}, \tag{27}$$

where $\mu_{x,y}$ is the surface area, SA_{xy} (Eqns 28–30), to volume, V_x (Eqns 31–33), ratio of material x with respect to the interface with material y. Interface surface area per cubic meter of litter layer is

$$SA_{lma} = SA_{ma} + SA_{la} = \mu\rho_{bulk}/\rho_{litter}, \tag{28}$$

$$SA_{la} = SA_{ml} = SA_{lma} \min\left\{\frac{l}{D_s\rho_{bulk}}, 1\right\}, \tag{29}$$

$$SA_{ma} = SA_{lma} - SA_{ml}, \tag{30}$$

where subscripts denote material type: *m*, litter, *l*, surface water, *a*, air. SA_{lma} is the combined surface area of the interfaces between liquid water and air, and litter and air, equal to the surface area of dry litter. The surface area of the liquid water interfaces, SA_{la} and SA_{ml}, are calculated on the assumption that the water forms a film of constant thickness, which covers the entire litter surface at capacity, and that for $D_s > l > 0$, SA_{la} and SA_{ml} are proportional to l. The volume of each material per cubic meter of layer is given by

$$V_m = \rho_{bulk}/\rho_{litter}, \tag{31}$$

$$V_l = l/\rho_{water}, \tag{32}$$

$$V_a = 1 - V_m - V_l. \tag{33}$$

The litter energy budget is

$$C_{h,m}\frac{\partial T_m}{\partial t} = \frac{1}{V_m}\left(\frac{\partial R_{net}}{\partial z} + \frac{\partial H_C}{\partial z}\right) - \mu_{m,a}H_{ma} - \mu_{m,a}\lambda E_{ma} - \mu_{m,l}H_{ml}, \tag{34}$$

where the individual terms are: (i) radiation; (ii) conduction; (iii) sensible heat flux to the air; (iv) latent heat flux due to water vapour flux to the air; (v) heat transfer between litter and surface water. $C_{h,m}$ is the volumetric heat capacity of the litter ($\mathrm{J\,K^{-1}\,m^{-3}}$), as a function of moisture content, and λ is the latent heat of vaporisation of water ($\mathrm{J\,kg^{-1}}$).

The free liquid water energy budget is

$$C_{h,l}\frac{\partial T_l}{\partial t} = -\mu_{l,a}H_{la} - \mu_{l,a}\lambda E_{la} + \mu_{l,m}H_{ml}, \tag{35}$$

where the individual terms are: (i) sensible heat flux to the air; (ii) latent heat flux due to evaporation; (iii) heat transfer between litter and surface water. $C_{h,l}$ is the volumetric heat capacity of water ($4.3 \times 10^6\,\mathrm{J\,K^{-1}\,m^{-3}}$).

The air energy budget is

$$\rho_{air}C_p\frac{\partial T_a}{\partial t} = \frac{1}{V_a}\frac{\partial H_T}{\partial z} + \mu_{a,m}H_{ma} + \mu_{a,l}H_{la}, \tag{36}$$

where the individual terms are: (i) vertical transfer; (ii) sensible heat flux from litter; (iii) sensible heat flux from surface water.

The litter moisture content is

$$\rho_{litter}\frac{\partial m}{\partial t} = -\mu_{m,a}E_{ma} - \mu_{m,l}E_{ml}, \tag{37}$$

where the individual terms are: (i) water vapour flux from litter to air; (ii) liquid water flux from litter to surface water. Note that (ii) is always negative or zero as surface water is absorbed by the litter.

Liquid water is

$$\frac{\partial l}{\partial t} = \frac{\partial D}{\partial z} + \mu_{l,m}E_{ml} - \mu_{l,a}E_{la}, \tag{38}$$

where the individual terms are: (i) drainage flux; (ii) litter water flux from surface water to litter; (iii) evaporation.

Specific humidity is

$$\rho_{air}\frac{\partial q}{\partial t} = \frac{1}{V_a}\frac{\partial E_T}{\partial z} + \mu_{a,m}E_{ma} + \mu_{a,l}E_{la}, \tag{39}$$

where the individual terms are: (i) vertical transfer; (ii) water vapour flux from litter to air; (iii) evaporation from surface water.

Boundary conditions

The upper boundary of the model is the atmosphere under the forest canopy, so energy and water fluxes across the top of the litter form the top boundary condition. For radiation, these fluxes are the downward short- and longwave radiation fluxes S_0 and L_0, and the upward fluxes, calculated by the radiation model. The liquid water flux is D_0, the rain rate. Fluxes of heat, $H_{T,0}$, and water vapour, $E_{T,0}$, are determined using flux-gradient (Stull 1988)

$$H_{T,0} = \rho_{air}C_pK_{T,0}(T_{a,1} - T_{a,0}), \tag{40}$$

$$E_{T,0} = \rho_{air}K_{T,0}(q_1 - q_0), \tag{41}$$

where T and q terms with the subscript 1 are the values of air temperature and specific humidity at the top of the litter layer and terms with the subscript 0 are values in the atmosphere. Turbulent conductance is (Viney 1991)

$$K_{T,0} = k^2U/(\ln(z_{screen}/z_0) - \Psi_m)(\ln(z_{screen}/7z_0) - \Psi_h), \tag{42}$$

where $k = 0.4$ is von Karman's constant, U is wind speed in the atmosphere ($\mathrm{m\,s^{-1}}$), z_{screen} is the height (m) at which atmospheric values of U, T_a, and q apply, and z_0 is the litter roughness length (m). The stability functions Ψ_m and Ψ_h are calculated from the bulk Richardson number using the equations of Viney (1991).

Similarly, energy and water fluxes between the litter and soil constitute the bottom boundary condition. Radiation fluxes are calculated by the radiation model from soil temperature and albedo. Liquid water reaching the bottom of the litter layer drains freely, being assumed to either infiltrate into the soil or be lost as runoff. Transfer of heat and water vapour between the soil and litter air spaces is computed using Eqns (9) and (10), assuming the soil heat and water vapour sources are at the top of the soil. Soil relative humidity, *RH*, is calculated from water content using the 'α' method (Viterbo and Beljaars 1995)

$$RH = \begin{cases} 0.5\left(1 - \cos\left(\frac{\pi}{c}\frac{\theta}{\theta_{cap}}\right)\right) & \theta < \theta_{cap} \\ 1 & \theta \geq \theta_{cap} \end{cases}, \quad (43)$$

where θ is the soil moisture content ($m^3\ m^{-3}$) and θ_{cap} is soil moisture content at field capacity ($m^3\ m^{-3}$). The correction, c, for the depth of the top layer of the soil model is set to 1 as the vapour source is assumed to be at the top of the soil. Upward transfer of liquid water by capillary action from the soil to litter is assumed not to occur, on the basis of laboratory experiments, which demonstrated that such transfer occurs only in the unusual situation that the soil is very damp and the litter very dry.

Parameters

Twenty-six parameters are required to run the model (Table 1). Values for all parameters were obtained without model fitting to the experimental datasets. Parameters were measured, obtained from the literature, or estimated from theoretical considerations. Where parameters were determined in the laboratory, samples from the Mt Wellington field site were used. These parameters were also applied to the second model run, for which suitable values were not available.

Litter layer depth was estimated in the field for each of the two experimental sites (Table 1). Bulk density was measured by weighing a known volume of litter. Litter density was measured by placing a known mass of litter in a graduated cylinder and measuring the volume of water required to bring the water level to 1 L. Surface area-to-volume ratio was determined by measuring the leaf area and mass of litter samples, and multiplying the ratio of these values by litter density. Leaves, bark, and twigs were treated separately, owing to their differing geometries, and a weighted average calculated using a leaf : bark : twig ratio of 5 : 1 : 4 (Ashton 1975). Litter characteristic length was estimated approximately by measuring the width of 10 *Eucalyptus obliqua* leaves at five evenly spaced locations along each leaf.

The parameters for the Nelson (1984) equilibrium moisture content model were those fitted by Anderson (1990) to moisture contents measured by King and Linton (1963*a*) for *E. obliqua* leaves. A litter surface conductance of $0.0006\ m\ s^{-1}$ was selected to correspond with the most commonly used fine fuel moisture response time of 1 h (e.g. Nelson 1991). Although a 1 h response time is consistent with observations of wetting and drying of *E. obliqua* leaves, bark, and twigs (King and Linton 1963*b*), it is conceivable that a different value should be used for other fuels. This possibility is explored below using parameter estimation. Liquid water absorption parameters were determined using laboratory measurements of the moisture content of *E. obliqua* leaves, bark, and twigs immersed in water (Fig. 2). The absorption model in Eqn (17) was fitted to the weighted average of the three series, using the same weights used to calculate surface area-to-volume ratio.

The radiation attenuation coefficient, γ, was estimated by measuring transmission of direct radiation through litter layers of varying thickness. Samples of *E. obliqua* litter of known leaf area were progressively added to the light box of a leaf area meter, and the fraction of the view not obscured by litter, equal to τ_1, was recorded. Results for leaves, bark, twigs, and mixtures of materials are shown in Fig. 3. An exponential decay model was fitted to the ensemble of results, giving $\gamma = 1.363$. Litter albedo was taken from field observations made by Silberstein *et al.* (2001).

Heat conductance values have been measured in an unspecified type of forest litter by Riha *et al.* (1980), $K_C = 0.1 + 0.03m$. The litter used had bulk density of $210\ kg\ m^{-3}$, very much higher than Eucalyptus leaf litter. For the present study, the values for wood are used, $K_C = 0.14 + 0.22m$, scaled by the volume fraction V_m of the litter layer (Pratt 1969). $K_{ml,H}$ was estimated as $700\ W\ m^{-2}\ K^{-1}$ assuming a conductivity of $0.35\ W\ m^{-1}\ K^{-1}$, the average of the conductivities of water, $0.59\ W\ m^{-1}\ K^{-1}$, and wood, $0.11\ W\ m^{-1}\ K^{-1}$, and a separation between heat reservoirs of 0.5 mm.

The maximum amount of water that can be held on the litter surface, D_s, was taken from laboratory measurements made by Putuhena and Cordery (1996). The drainage coefficient, D_a, was estimated by tuning a numerical solution of Eqn (38), with terms (ii) and (iii) set to zero, to reproduce the difference between D_s and l observed by Putuhena and Cordery (1996) with rainfall rates of 48 and $60\ mm\ h^{-1}$.

Matthews (2005) measured the bulk water vapour conductance of *E. globulus* leaf litter layers, and also the ratio of top to bottom half conductance in a 5 cm-deep leaf litter layer. D_{T0} and χ were determined at each of the wind speeds used in the laboratory experiments (0, 0.8, 2.2, and $3.3\ m\ s^{-1}$) by fitting the top and bottom half conductances, obtained by reducing Eqn (9) from continuous to discrete form, to Matthews' (2005) observations. D_{T0} and χ were then modelled as functions of wind speed using a least squares fit

$$D_{T0} = D_{T0,a} \cdot \exp(U \cdot D_{T0,b}), \quad (44)$$

$$\chi = \chi_a + U \cdot \chi_b, \quad (45)$$

where $D_{T0,a}$, $D_{T0,b}$, χ_a, and χ_b are regression coefficients. Values for soil field capacity, $\theta_{cap} = 0.3\ m^3\ m^{-3}$, and albedo, $\alpha_s = 0.2$ were taken from Viterbo and Beljaars (1995).

Forest floor roughness length was estimated from wind profiles measured in Jarrah and Karri forest in Western Australia (I. Knight, personal communication). The fitted value, $z_0 = 0.01$ m was similar to that measured in pine forest by Lee and Black (1993). Screen height was the height at

Table 1. Model parameters

Twenty-six parameters are required to run the model. Listed parameter values were determined from laboratory measurement, the literature, or theoretical considerations. The relative sensitivity of the model to each parameter was determined using Eqns (47) and (48). Parameters with relative sensitivity < 0.1 are indicated by dashes

Group	Description	Symbol	Unit	Parameter value		Relative sensitivity		
				Perup	Mt Wellington	S at Perup	S_T at Mt Wellington	P_T at Mt Wellington
Litter dimensions	Litter layer depth	h	m	0.02	0.04	–	–	−6.5
	Litter layer bulk density	ρ_{bulk}	kg m^{-3}	62	62	–	–	−8.2
	Litter density	ρ_{litter}	kg m^{-3}	550	550	0.4	0.2	0.9
	Litter surface area-to-volume ratio	μ	m^{-1}	3000	3000	−0.5	−0.3	−1.1
	Litter characteristic length	d	m	0.03	0.03	–	0.1	0.5
Litter moisture	Nelson (1984) model parameters	A		5.2	5.2	1.2	0.1	1.2
		B		−19	−19	−6.4	–	−0.7
	Litter surface conductance	$K_{ma,E}$	m s^{-1}	0.0006	0.0006	−0.5	−0.2	−0.2
	Saturation moisture content	m_{sat}	kg kg^{-1}	1.4	1.4	–	–	–
	Liquid water absorption parameters	L_a	kg kg^{-1}	0.23	0.23	–	5.3	–
		L_b	kg kg^{-1}	−1.63	−1.63	–	−3.7	0.2
Radiation	Litter albedo	α_l		0.27	0.27	–	–	0.4
	Radiation attenuation coefficient	γ		1.363	1.363	–	0.2	0.2
Conduction	Litter heat conductivity as a function of moisture content	$K_{C,slope}$	W m^{-1} K^{-1}	0.2	0.2	–	–	–
		$K_{C,intercept}$	W m^{-1} K^{-1}	0.14	0.14	–	–	–
	Litter-to-water heat conductivity	$K_{ml,H}$	W m^{-2} K^{-1}	700	700	–	–	–
Drainage	Rainfall storage capacity	D_s	kg kg^{-1}	1.153	1.153	–	2.5	−0.6
	Drainage coefficient	D_a	s^{-1}	0.00003	0.00003	–	–	–
Vertical mixing	Diffusivity at top of litter layer	$D_{T0,a}$	m^2 s^{-1}	0.00002	0.00002	–	–	−0.9
		$D_{T0,b}$	s m^{-1}	2.60	2.60	–	–	−2.3
	Attenuation coefficient for D_T	χ_a		2.08	2.08	–	–	0.5
		χ_b	s m^{-1}	2.38	2.38	–	–	–
Soil	Soil albedo	α_S		0.2	0.2	–	–	–
	Soil field capacity	θ_{cap}	m^3 m^{-3}	0.3	0.3	–	–	−0.1
Top boundary	Aerodynamic roughness length	z_0	m	0.01	0.01	–	−0.2	−0.9
	Screen height	z_{screen}	m	2	0.15	–	0.2	1.5

which atmospheric measurements were made for each field campaign.

Implementation

The equations were solved at five equally spaced nodes in the litter layer at 1 h intervals. Eqns (34–39) were solved using backward finite differences. Simultaneous solutions to all 30 equations were determined numerically using the Newton-Raphson method, with a line search used to determine optimum step size. The initiation of rainfall with a 1 h time step resulted in large, rapid changes in l, as the litter layer can be brought to capacity, D_s, in less than 1 h even at moderate rainfall rates. To ensure model stability when any of the drainage terms D_i were non-zero, a preliminary solution to Eqn (38) was determined before solving the full set of equations.

At each time step, the model predicts a 30-element state vector (three energy and three moisture contents at five

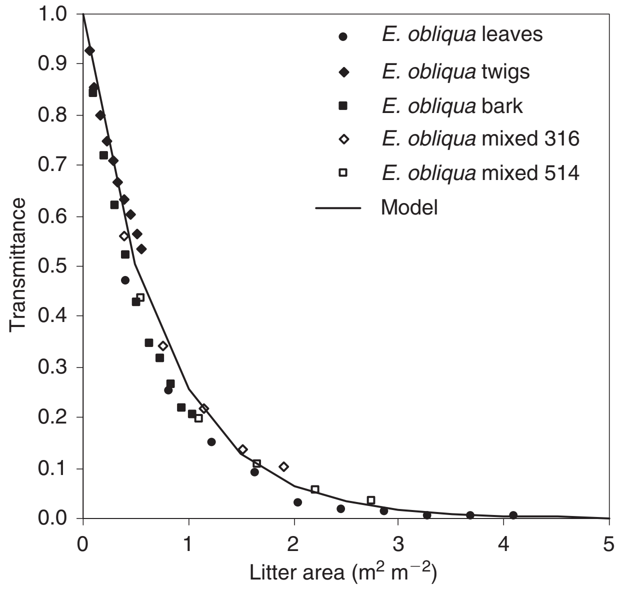

Fig. 3. Shortwave transmittance of *Eucalyptus obliqua* litter layers. Litter area is the single-sided surface area of the litter elements (leaves, bark, twigs), when non-overlapping, per m^2 of ground. Two ratios of leaves : bark : twigs were used in the mixed samples: 3 : 1 : 6 and 5 : 1 : 4. The model is a least-squares fit of Eqn (1) to all measurements.

nodes). For comparison with field measurements, the state vector was reduced to four quantities:

1. Surface moisture content, S: the average of m in the top 8 mm of the litter.
2. Profile moisture content, P: the average of m through the entire litter layer.
3. Total surface moisture, S_T: the total water content of the top 8 mm of the litter, including both m and l.
4. Total profile moisture content, P_T: the total water content of the entire litter layer.

The model was implemented in Visual Basic for Applications, using an Excel spreadsheet to store model inputs and outputs. One day was simulated in around 5 s on a Windows PC with a 2.4 GHz processor.

Model runs

The model was tested against two sets of observations, representing two typical fuel moisture prediction tasks: prediction of minimum and maximum fuel moisture in response to changing relative humidity on a dry day, and wetting and drying in response to rainfall. The first model run used measurements from Eucalyptus mallee scrub near Perup, in south-west Western Australia, collected after 12 rain-free days. The second used measurements from an experiment in *E. obliqua* forest on the foothills of Mt Wellington in Tasmania during which 8 mm of rain fell over 3 days.

Perup

Fuel moisture samples were collected over 4 days in Eucalyptus mallee scrub in south-west Western Australia by the Western Australian Department of Conservation and Land Management (McCaw 1998). The scrub was 4 m tall with 40% canopy closure, under which was a shrub layer 0.7 m tall. The litter layer was 10–20 mm deep, consisting of leaves from the Eucalypts and shrubs. Three samples of surface litter were collected every 1 h from 1100 hours on 15 April 1996 to 1100 hours on 18 April 1996, except for a break from 0100 hours to 0500 hours on 18 April 1996. Fuel moisture content was determined by oven drying. Atmospheric conditions were measured using a 2 m automatic weather station. Further details of the measurements are given by McCaw (1998). These measurements have also been used by Catchpole *et al.* (2001), who fitted a model similar to Nelson's (1991) to the observations.

Soil temperature and moisture content were not measured during the experiment. In order to run the model, it was assumed that soil temperature was equal to screen level air temperature, and that the soil was sufficiently dry that the water vapour flux from the soil was zero.

The conditions at Perup represented a typical sequence of fuel moisture content during burning conditions (Fig. 4*a*). Fuel moisture increased and decreased with relative humidity: the lowest FMC occurred during mid-afternoon and the highest just before dawn (Fig. 4*b*). In this situation, the most important information that the model must predict is the minimum and maximum FMC on each day and the times these occur.

The model correctly reproduced the decreasing amplitude of the diurnal cycle of S over the course of the experiment. The largest discrepancy was minimum S on 15 April 1996, which was under-predicted by 4%. All remaining extrema were within 1.5% of observations and the times of the extrema were also correct. However, the model lagged behind the observations during steep changes in S on the evening of 15 April 1996 and the morning of 17 April 1996. The lag on the first evening was not due to the under-prediction of minimum S, as the lag occurred even if the model was run from 1800 hours and initialised with observed $S = 11\%$.

Mt Wellington

Fuel moisture samples were collected from 6 January 2004 to 9 January 2004 in *E. obliqua* forest on the foothills of Mt Wellington in Tasmania. The forest was 15 m-tall trees with a sparse shrub layer less than 0.5 m tall. The litter layer was 30–50 mm deep, consisting of leaves, bark, and twigs from the trees, and twigs from the shrubs. Three samples each of surface and profile litter were collected every 2 h from 0600 to 2000 hours each day. Any water on the surface of the litter was not removed when the samples were collected,

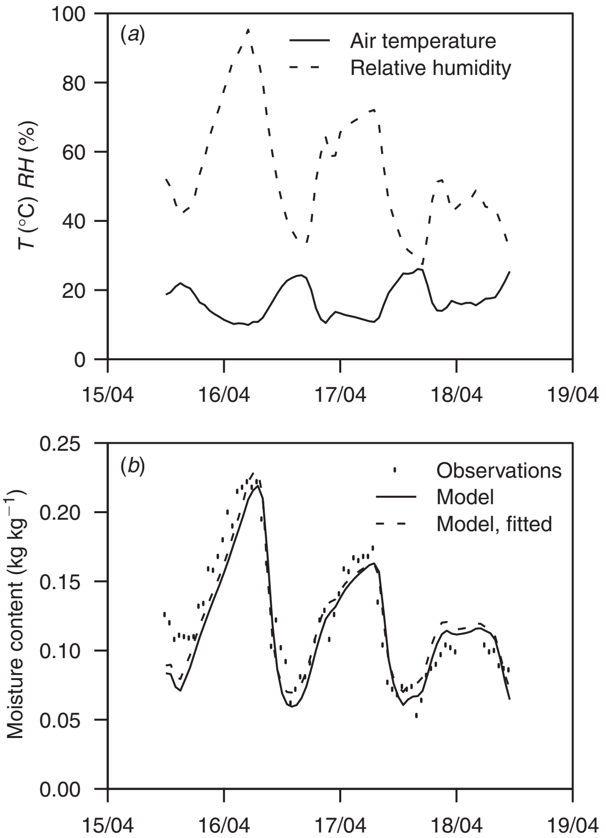

Fig. 4. (*a*) Weather conditions during fuel moisture sampling experiments at Perup. Measurements are 1 h averages at screen height. (*b*) Observations and predictions of surface moisture content at Perup. Solid lines are model predictions made using parameters listed in Table 1. Dashed lines are model predictions after parameter estimation.

so the measurements were of S_T and P_T. Fuel moisture content was determined by oven drying. Atmospheric conditions were measured using sensors mounted at 0.2 m. Soil temperature was measured continuously at 1 cm depth and moisture content in the top 1 cm of the soil was sampled gravimetrically at 0600 and 2000 hours each day.

During the experiment, 5 mm of rain fell on the morning of 7 January 2004, 3 mm on 8 January 2004 and trace rainfall (<0.2 mm) on 9 January 2004 (Fig. 5*a*). As a result, both S_T and P_T were dominated by wetting and drying associated with rain after the first dry day of the experiment (Fig. 5*b*,*c*). These results were typical of conditions encountered in spring or autumn when planning prescribed burns. In this situation, the most important predictions are the amount of wetting due to rain and the time at which the litter layer again becomes flammable.

Results from the model run were mixed. The timing of the minima in S and P on the first day were correct but modelled S was 1.5% below the observed value and P was 2% too low. In the rain-affected part of the experiment, three wetting and drying cycles were identified, (1) from 0600 hours on 7 January 2004 to 0600 hours on 8 January 2004; (2) from 0600 hours on 8 January 2004 to 0700 hours on 9 January 2004; and (3) from 0700 hours on 9 January 2004 to the end of the experiment. During each cycle, total profile moisture content was simulated well. Maximum P_T at the cessation of rain was within 12% of the observed value and minimum P_T

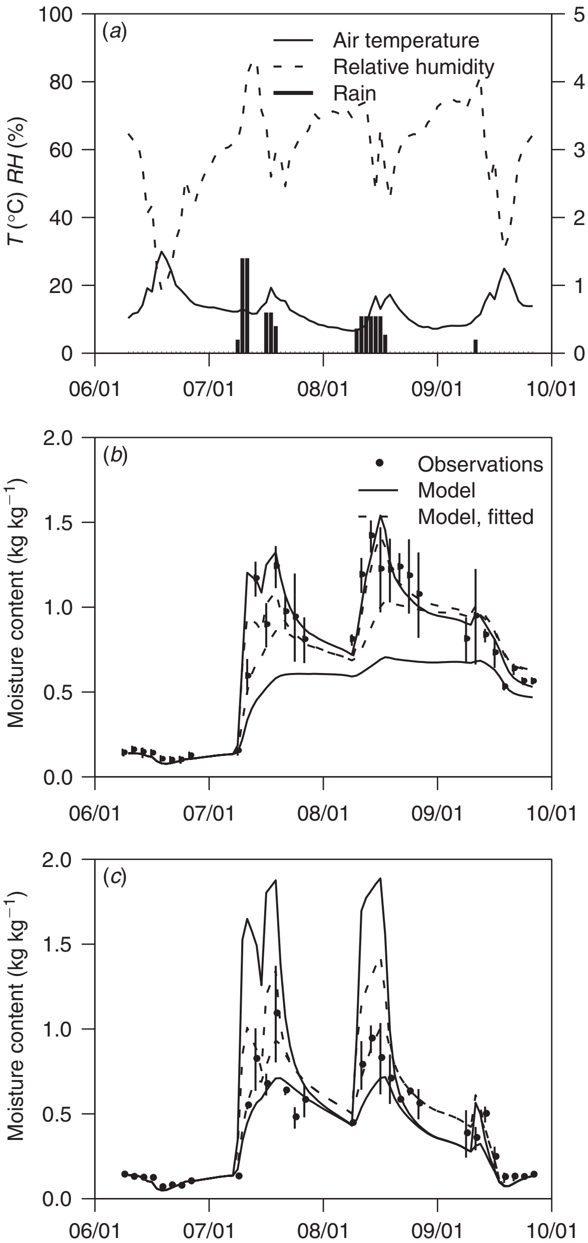

Fig. 5. (*a*) Weather conditions during fuel moisture sampling experiments at Mt Wellington. Measurements are 1 h averages at screen height. Observations and predictions of (*b*) profile moisture, and (*c*) surface moisture content at Mt Wellington. Vertical lines are one standard deviation. Solid lines are model predictions made using parameters listed in Table 1. Dashed lines are model predictions after parameter estimation. Where there are two solid or dashed lines in (*b*) and (*c*), the upper line is total moisture content and the lower line is moisture content held in the litter solids. The distance between the lines is the amount of water on the litter surface.

at the end of the cycles was within 10% of measurements. S_T was grossly over-predicted during the wetting phase of all three cycles, by as much as 95%. However, the large amount of excess free water quickly evaporated once the rain ceased. In the latter parts of the first two drying cycles, from 2000 hours to 0600 hours the next morning, S_T was closer to the observed values and finished the drying cycles within 7% of measured S_T. The almost complete evaporation of free water at the model surface by 2000 hours on 7 January 2004 and 8 January 2004 matched observers' notes that the surfaces of the surface litter were free of water whereas the profile was still very wet at these times. In the third drying cycle, the model predicted S_T to drop more rapidly than observed, and by early evening, model S_T was responding to changing relative humidity, whereas measurements remained at constant moisture content.

Model sensitivity

The sensitivity of the model to its parameters was examined by calculating the relative change in model output that results from a change in each of the 26 parameters. Relative sensitivity, λ_i, of model output Q to parameter p_i is defined by (Esprey *et al.* 2004)

$$\lambda_i = \frac{p_i}{Q}\frac{\partial Q}{\partial p_i}. \tag{46}$$

Relative sensitivity can be calculated using a finite difference approximation

$$\lambda_i = \frac{p_{i,0}}{Q}\frac{Q_+ - Q_-}{2\delta_p}, \tag{47}$$

where Q is calculated using the set of parameters listed in Table 1, $p_{i,0}$ is the unperturbed value of the parameter of interest, Q_+ is calculated by running the model with $p_i = p_{i,0} + \delta_p$, and Q_- using $p_i = p_{i,0} - \delta_p$. Parameter perturbation, δ_p, was arbitrarily chosen to be 20% of p_i.

The variable Q can be any model output of interest. For the present study, in which correctly predicting cycles in FMC rather than just mean values was important, Q was chosen to be the sum of square errors (SSE) of the model output with respect to the observations

$$Q = SSE = \sum_{i=1}^{n}(X_i - \hat{X}_i)^2, \tag{48}$$

where X_i is the ith of n measured values and $\hat{X}_i$ is the model prediction of X_i. For the Perup model run, SSE was calculated using $X = S$, whereas at Mt Wellington separate sensitivity studies were made for $X = S_T$ and $X = P_T$.

SSE for the Perup run was most sensitive to the fuel relative humidity parameters A and B, and also to litter density, ρ_{litter}, surface area-to-volume ratio, μ, and surface conductance, $K_{ma,E}$ (Table 1). Sensitivity was negligible for all other parameters. Under dry conditions, the litter moisture budget equation reduces to (Eqns 15 and 37)

$$\frac{dm}{dt} = -\rho_{air}\frac{\mu_{m,a}K_{ma,E}}{\rho_{litter}}(RH \cdot q_{sat} - q). \tag{49}$$

Model sensitivity to A and B results simply from the response of m to equilibrium moisture content, expressed here through fuel relative humidity. The three other parameters (ρ_{litter}, μ, and $K_{ma,E}$) determine the rate of response of m to the humidity difference between the fuel and air. As Eqn (49) makes clear, the model depends equally on all three parameters.

Error in S_T at Mt Wellington was most sensitive to the parameters that determined interception and absorption of rainfall, D_s, L_a, and L_b. SSE was not sensitive to saturation moisture content, m_{sat}, as the fuel was not wet long enough to reach saturation. SSE was also marginally sensitive to the fuel relative humidity and response rate parameters due to the inclusion of the single dry day at the start of the experiment. Finally, SSE was marginally sensitive to the radiation attenuation coefficient, γ, litter characteristic length, d, roughness length, z_0, and screen height, z_{screen}, through their effects on the evaporation rate of water from the litter surfaces.

Error in P_T at Mt Wellington was sensitive to a wider array of parameters than S_T at either site. SSE was most sensitive to litter layer bulk density, ρ_{bulk}, and depth, h. The rainfall recorded during the experiment was not sufficient to fill the model litter layer to capacity, and hence ρ_{bulk} and h, in conjunction with D_s, determined what fraction of litter capacity the rain represented. The effect of ρ_{bulk} on litter capacity also affected the vertical distribution of intercepted precipitation through the depth of the litter layer, which in turn affected the drying rate as water can be removed more quickly from the top of the litter layer than the bottom. Sensitivity of the model to the rate of removal of water vapour was also manifest in sensitivity to litter dimensions, ρ_{litter}, μ, and d, and to parameters controlling vertical mixing, $D_{T0,a}$, $D_{T0,b}$, χ_a, χ_b, z_0, and z_{screen}. SSE in P_T was also sensitive to the fuel relative humidity parameters A and B, but it was not clear why sensitivity for these parameters was higher for P_T than S_T. SSE was slightly sensitive to radiation parameters α_l and γ through the effect of the radiation budget on litter temperature and hence evaporation rate.

Parameter estimation

Discrepancies between model predictions and experimental observations may be caused by errors in parameterisation, inadequacies in the model structure, and experimental factors such as deficiencies in measurements of boundary conditions or inherent variability in FMC measurements. Parameter estimation is a useful way to examine whether more accurate specification of parameters can improve model performance, and may also reveal problems with model structure.

Best fit parameters were obtained by varying parameters to minimise an objective function

$$\chi^2(X) = \sum_{i=4}^{n} \frac{(X_i - \hat{X}_i)^2}{\sigma_i^2}, \tag{50}$$

where σ_i is the standard error in measured quantity X_i, and $\hat{X}_i$ is the model prediction of X_i with a given set of parameters. To avoid dependence of the result on initial conditions, the first three observations were excluded. For the Perup run, the objective function was calculated using surface moisture content, $\chi^2(S)$, and for Mt Wellington, both total surface and profile moisture content were used, with $\chi^2 = \chi^2(S_T) + \chi^2(P_T) \cdot \chi^2$ was minimised using the Levenberg-Marquardt method (Press *et al.* 1992).

Model performance before and after parameter estimation was assessed quantitatively using the absolute error (AE) and root mean squared error (RMSE) (Catchpole *et al.* 2001)

$$AE = \sum_{i=4}^{n} |X_i - \hat{X}_i|/n, \tag{51}$$

$$RMSE = \left(\sum_{i=4}^{n} (X_i - \hat{X}_i)^2/n \right)^{1/2}, \tag{52}$$

where symbols are as for Eqn (50). As with the sensitivity study, AE and RMSE were calculated for S at Perup and for S_T and P_T at Mt Wellington.

For the Perup case, three parameters to which the model was sensitive were fitted, the two fuel relative humidity parameters, A and B, and the litter surface conductance, $K_{ma,E}$. The remaining two parameters, ρ_{litter}, and μ, were not fitted as they could not be determined independently of $K_{ma,E}$. Fitted values were: $A = 5.6 \pm 0.2$, $B = -22 \pm 1.7$, $K_{ma,E} = 0.0012 \pm 0.0002$. The largest change was to $K_{ma,E}$, which doubled, whereas only small adjustments were made to A and B. These changes resulted in small decreases in AE, from 1.4% to 1.2%, and RMSE, from 1.7% to 1.5%. These figures are similar to those obtained by Catchpole *et al.* (2001) when fitting a modification of Nelson (1991) to the same dataset, AE = 1.3%, RMSE = 1.6%. Comparing the fitted and original models (Fig. 4*b*) shows only small changes. The fitted model reduces the under-prediction of minimum S on 15 April 1996 by 0.8% and also reduces the lag of the model behind observations on the evening of 15 April 1996. These improvements come at the expense of less accurate predictions of maximum S on the evenings of 15 April 1996 and 17 April 1996, and minimum S in 16 April 1996, in each case by around 1%.

In its present form, the model cannot reproduce the higher minimum S on 15 April 1996. Unfortunately there is not sufficient information available from the experimental measurements to determine whether this difference is the result of a deficiency in the model structure or some experimental factor, such as variation in the shading of the samples collected on the first and subsequent days.

For the Mt Wellington run, only those parameters to which S_T was most sensitive were fitted, L_a, L_b, and D_s. This limited set was chosen because P_T was satisfactorily simulated by the model. Fitted parameter values were: $L_a = 0.48 \pm 0.23$, $L_b = -3.88 \pm 0.75$, $D_s = 0.4 \pm 0.1$. These changes imply faster absorption of water and a 65% reduction in water storage capacity (Fig. 5*b*,*c*). The new parameters resulted in large changes in errors in S_T, AE was reduced from 45.7% to 21.8%, and RMSE changed from 27.5% to 14.1%. These reductions were achieved with only small changes in the error statistics for P_T. AE increased from 9.1% to 9.4% and RMSE decreased from 14.0% to 11.6%. The reduction in D_s reduced the over-estimation of S_T during rain but maximum S_T during the second wetting cycle was still 50% too high. A higher rate of absorption of water compensated for a lower amount of water intercepted by the litter, and in fact S_T at the end of the first two drying cycles was higher than with the original parameters. Minimum S_T at the end of the drying cycles was within 6% of observations, similar to results achieved with the original parameters. As expected from the sensitivity study, the changes in the three fitted parameters produced smaller changes in P_T than in S_T. However, there was a large change in the balance of the m and l values that comprise P_T, with the faster absorption rate in the fitted model meaning that a much larger proportion of P_T was water in the litter than in the original model. This change reduced the drying rate during all three drying phases and increased P_T at the end of drying in the second and third cycles. P_T was lower at the end of the first cycle than in the original model because maximum P_T during the first rainfall was reduced by 20%.

The results from fitting the model to the Mt Wellington case indicate that the present model structure may be able to realistically represent wetting of the surface litter with suitable parameters. However, the large difference between the preliminary measurements of these parameters and the fitted values indicates that more experimental investigation of interception and absorption of rain by the litter would be wise. This should include examination of whether the laboratory results shown in Fig. 2 are applicable in the field where the litter is wet by rainfall rather than immersion in water. This issue notwithstanding, the robustness of the drying results to widely varying values of the wetting parameters shows that the present model structure will be useful, subject to further field validation.

Conclusion

The physical processes that determine fuel moisture in forest litter are a complex interaction of transfers of radiation, heat, and water. The present paper has presented the first comprehensive process-based model of fuel moisture suitable for use in both wet and dry conditions. The model performed well in dry conditions, predicting minimum and maximum FMC to within 1.5% in most cases, and also correctly predicting the timing of extrema. Under wet conditions, the model correctly represented the wetting and drying of profile FMC to within 10%. Surface FMC was over-predicted during rain but drying after rain was better represented, with predicted values at the end of drying cycles within 10% of observations. Parameter estimation indicated that correct prediction of surface FMC during rain may be limited by the model structure. More experimental research on interception and absorption of rainfall would be valuable for future model development. Although the three days of rain that affected measurements used to test the model were sufficient to establish that the model responded to rain in the correct manner, excepting surface wetting, the field observations covered only a very narrow range of drying conditions. To better validate the model, it should next be tested against a larger dataset that encompasses a wider range of weather conditions.

The model has scope for application in forest types other than the Eucalypt forest and mallee examined in the present study. The model should, in principle, be applicable in any forest type if the correct set of parameters is specified. The sensitivity study showed that under dry conditions site-specific values of only those parameters that affect vapour exchange need to be determined. Values of these parameters have already been determined for many species (Anderson 1990). Under wet conditions, the model was sensitive to a larger group of parameters, and adaptation of the model to new locations would require more effort.

Application of the model requires the specification of boundary conditions at frequent intervals. Also, three of the boundary conditions, soil temperature, soil moisture, and solar radiation, are not normally measured in routine fire weather observations. Thus, the transfer of the model from research to operational use will require the development of tools to predict the necessary boundary conditions from more readily available data sources. Possible approaches include coupling the fuel moisture model to a numerical weather prediction model or coupling the fuel moisture model to a soil model and using weather observations to drive both models. Application of the model in operational situations will be the subject of future research.

Acknowledgements

Lachie McCaw of the Western Australian Department of Conservation and Land Management conducted the experimental work at Perup, with the assistance of Bob Smith and John Neal. Juanita Myers of CSIRO Forestry and Forest Products assisted with collection of samples for the Mt Wellington dataset. Alen Slijepcevic of Forestry Tasmania contributed weather observations to the Mt Wellington dataset and assisted with site selection.

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Appendix 1. List of symbols

Subscripts *x* and *y* indicate one of the three materials comprising the litter layer: litter, *m*, liquid water on litter surfaces, *l*, or air, *a*

Symbol	Description	Unit
α_l	Litter albedo	
α_S	Soil albedo	
γ	Radiation attenuation coefficient	
θ	Soil moisture content	$m^3\ m^{-3}$
θ_{cap}	Soil field capacity	$m^3\ m^{-3}$
κ_h	Thermal diffusivity of dry air	$2.08 \times 10^{-5}\ m^2\ s^{-1}$
κ_v	Diffusion coefficient for water vapour in air	$2.34 \times 10^{-5}\ m^2\ s^{-1}$
λ	Latent heat of vaporisation of water	$2.45 \times 10^6\ J\ kg^{-1}$
λ_ι	Relative sensitivity of model	
Λ	Leaf area index of one model layer	$m^2\ m^{-2}$
μ	Litter surface area-to-volume ratio	m^{-1}
$\mu_{x,y}$	Surface area-to-volume ratio of *x* for fluxes to *y*	m^{-1}
ρ_{air}	Air density	$kg\ m^{-3}$
ρ_{bulk}	Litter layer bulk density	$kg\ m^{-3}$
ρ_{litter}	Litter density	$kg\ m^{-3}$
σ	Stefan-Boltzmann constant	$5.67 \times 10^{-8}\ W\ m^{-2}\ K^{-4}$
σ_ι	Standard error in a measured quantity	
τ	Transmittance	
χ	Rate of attenuation of D_T	
Ψ	Stability function	
A	Nelson (1984) model parameter	
B	Nelson (1984) model parameter	
$C_{h,l}$	Volumetric heat capacity of water	$4.3 \times 10^{-6}\ J\ m^{-3}\ K^{-1}$
$C_{h,m}$	Volumetric heat capacity of litter	$J\ m^{-3}\ K^{-1}$
C_p	Specific heat of air	$1004.5\ J\ kg^{-1}\ K^{-1}$
d	Litter characteristic length	m
D	Drainage flux	$kg\ m^{-2}\ s^{-1}$
D_0	Rainfall rate	$kg\ m^{-2}\ s^{-1}$
D_a	Drainage coefficient	$kg^{-1}\ m^4\ s^{-1}$
D_p	Fraction of drainage intercepted	
D_s	Rainfall storage capacity	$kg\ kg^{-1}$
D_T	Turbulent diffusivity of air	$m^2\ s^{-1}$
E_T	Water vapour flux due to vertical mixing	$kg\ m^{-2}\ s^{-1}$
E_{xy}	Water vapour flux from *x* to *y*	$kg\ m^{-2}\ s^{-1}$
h	Litter layer depth	m
$F_{i,j}$	View factor for longwave radiation calculations	
H_C	Conductive heat flux	$W\ m^{-2}$
H_T	Heat flux due to vertical mixing	$W\ m^{-2}$
H_{xy}	Heat flux from *x* to *y*	$W\ m^{-2}$
k	von Karman constant	0.4
K_C	Thermal conductance of litter	$W\ m^{-1}\ K^{-1}$
$K_{la,E}$	Conductance for evaporation of free water	$m\ s^{-1}$
$K_{la,H}$	Conductance for heat flux from free water to air	$m\ s^{-1}$
$K_{ml,H}$	Litter-to-water heat conductance	$W\ m^{-2}\ K^{-1}$
$K_{ma,E}$	Litter surface conductance	$m\ s^{-1}$
$K_{ma,H}$	Conductance for heat flux from litter to air	$m\ s^{-1}$
$K_{T,0}$	Turbulent conductance for fluxes from litter layer to atmosphere	$m\ s^{-1}$
l	Amount of water on litter surfaces	$kg\ m^{-3}$
L_0	Downwelling longwave irradiance at the top of the litter layer	$W\ m^{-2}$
L_a	Liquid water absorption parameter	$kg\ kg^{-1}$
L_b	Liquid water absorption parameter	$kg\ kg^{-1}$
L_{dn}	Downwelling longwave irradiance	$W\ m^{-2}$
L_{up}	Upwelling longwave irradiance	$W\ m^{-2}$
m	Litter moisture content	$kg\ kg^{-1}$
m_e	Equilibrium moisture content	$kg\ kg^{-1}$
m_{sat}	Saturation moisture content	$kg\ kg^{-1}$
M	Molecular mass of water	$18.0153\ g\ mol^{-1}$
N	Number of model layers in the litter bed	
p_i	An arbitrary model parameter	
P	Profile moisture content	$kg\ kg^{-1}$
P_T	Total profile moisture content	$kg\ kg^{-1}$
q	Specific humidity	$kg\ kg^{-1}$
q_{sat}	Saturation specific humidity	$kg\ kg^{-1}$
Q	An arbitrary model output	
R	Universal gas constant	$8.314\ J\ mol^{-1}\ K^{-1}$
RH	Relative humidity	
R_{net}	Net radiation	$W\ m^{-2}$
S	Surface moisture content	$kg\ kg^{-1}$
S_0	Downwelling shortwave irradiance at the top of the litter layer	$W\ m^{-2}$
S_{dn}	Downwelling shortwave irradiance	$W\ m^{-2}$
S_T	Total surface moisture content	$kg\ kg^{-1}$
S_{up}	Upwelling shortwave irradiance	$W\ m^{-2}$
SA_{xy}	Surface area of the interface between *x* and *y* per m^3 of litter layer	$m^2\ m^{-3}$
t	Time	s
T_a	Air temperature	K
T_l	Water temperature	K
T_m	Litter temperature	K
T_s	Soil temperature	K
U	Wind speed	$m\ s^{-1}$
V_x	Volume fraction of *x*	$m^3\ m^{-3}$
X_i	An arbitrary measured quantity	
$\hat{X}_i$	Model prediction of measured X_i	
z	Height above soil surface	m
z_0	Aerodynamic roughness length	m
z_{screen}	Screen height	m