

Process based modelling of fine fuel moisture

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Abstract

The moisture content of fine fuels (FMC) is an important variable determining fire ignition and behaviour. Modelling of FMC is necessary for predicting the spread of wild fires and for planning prescribed burning. FMC prediction models currently in use in Australia are empirical, relating FMC or changes in FMC to weather variables through functions derived from field measurements. Since these models function as black boxes it is not possible to satisfactorily include new physical processes in the models or to reapply them to new locations without rebuilding the entire model. A modelling project at CSIRO Forestry and Forest Products is attempting to overcome these limitations by developing a new process based model for fine fuel moisture. A process based model explicitly represents the physical processes in a fuel bed. So it can be applied in many locations by variation of parameters, and may also be incrementally improved as knowledge of fuel moisture physics advances. This paper reviews fuel moisture physics, present an outline of what we hope to achieve with the new model, and discusses progress to date.

1. Introduction

Two fire behaviour prediction systems are presently used in Australia: the McArthur Forest Fire Danger Meter (FFDM, McArthur 1967), used in the eastern states, and the Forest Fire Behaviour Tables (FFBT, Sneeuwjagt and Peet 1998), used in Western Australia. Both systems contain an empirical model for predicting fine fuel moisture. The FFDM models FMC as a function of air temperature and relative humidity. Drought factor, a measure of the fraction of the fuel bed that is available for combustion, is modelled as a function of rainfall amount and time since rain. The FFBT system differs slightly, modelling changes in FMC as a function of air temperature, relative humidity, and rainfall, and adjusts this for forest type. Similar empirical models are used by fire management agencies around the world, many of which are variants of the Canadian Fine Fuel Moisture Code (van Wagner 1987). A notable exception is a physical model for hazard rods developed by Nelson (2000).

Empirical models relate inputs (weather) to outputs (fuel moisture) using functions derived from field observations by using statistical methods. Empirical models do not attempt to directly model the physical processes that determine fuel moisture. While this approach to predicting FMC produced useful models at a time when modelling of forest micrometeorology was in its infancy (Pitman 2003), empirical models have two important limitations. Firstly, it is not possible to take account of variables which were not included in the original model but which are known to have an effect on FMC, e.g. aspect and canopy density. Secondly, it is not possible to make use of advances in understanding of fuel moisture physics to improve an empirical model. For example, the FFDM indicates that drought factor increases at a constant rate per

day, regardless of weather conditions, while there is now sufficient understanding of evaporation from litter beds to develop a more sophisticated model.

To overcome these limitations CSIRO Forestry and Forest Products is developing a new process based fine fuel moisture model. A process based model explicitly models the physical processes which determine FMC. This type of model offers the following significant advantages over an empirical model. The 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 not previously considered important for predicting fire behaviour, such as e.g. near surface fuels can be included.

The remainder of the paper reviews fuel moisture physics, outlines the structure of the new model, discusses possible applications of the model, and describes progress so far.

2. Fuel moisture physics

Dead fine fuels can be stratified into 5 types:

- *Elevated fuels*: bark on trees and bark, leaves, and twigs suspended in tree limbs and tall shrubs,
- *Near surface fuels*: bark, leaves and twigs suspended on grasses, small shrubs, and heavy fuels,
- *Grass fuel*: cured grasses,
- *Surface fuel*: fine fuels at the top of the litter bed,
- *Profile fuel*: all fine fuels from the top of the litter bed to the soil.

The profile fuel is not homogeneous as it exhibits a vertical transition from freshly fallen litter at the top of the layer, through partially decomposed litter, to a fully decomposed organic soil or 'duff' layer. The thickness of these layers depends on accumulation and decomposition rates.

Fuel moisture responds to changes in temperature and relative humidity and the presence of water on the fuel surface. In the litter bed, these in turn depend on radiation, precipitation, and heat and water vapour fluxes. Process directly affecting the fuel particles have received the most attention in prior modelling efforts with much less attention payed to litter bed processes (Viney 1991). Fortunately, most of the litter bed processes have been treated by researchers in other fields, as described below. In the following paragraphs a description of each process is presented.

2.1 Vapour exchange

Vapour exchange is the physical process that has received the most attention in studies of fuel moisture (Viney 1991). Vapour exchange occurs when the water vapour pressure at the surface of the fuel differs from that of the surrounding air. Two processes occur during vapour exchange (Byram 1963): exchange of water vapour across the surface of the fuel particle and diffusion within the fuel particle in response to the change at the surface. Byram (1963) assumed that vapour exchange was governed by internal diffusion, with the moisture content at the surface of the fuel adjusting instantaneously so that the vapour pressure difference with the atmosphere was always zero. This zero gradient moisture content is known as the equilibrium moisture content (EMC). By integrating the diffusion equation over fuel particles of

various shapes, Byram (1963) showed that changes in fuel moisture, $m(t)$ due to vapour exchange could be represented as :

$$m(t) = m_e + (m_{(0)} - m_e)e^{-t/\tau}$$

Where m_e is the equilibrium moisture content, $m_{(0)}$ is the moisture content at time, $t = 0$, and τ is a response time. The fuel is then characterised by its equilibrium moisture content, as a function of temperature and relative humidity, and a response time. This equation has been used in some FMC models (e.g. Nelson 1991, van Wagner 1987). EMC and response times have been determined for many northern hemisphere species (Anderson 1990a; Anderson 1990b; Anderson *et al.* 1978; van Wagner 1972; van Wagner 1979) but only a few measurements have been made for Australian species (Catchpole *et al.* 2001; King and Linton 1963a; King and Linton 1963b). Experimental work is currently underway to determine EMC and τ for *Eucalyptus obliqua* and *E. globulus*.

2.2 Precipitation

It has long been recognised that forest litter layers can intercept and store large quantities of precipitation (Walsh and Voigt 1977). Precipitation initially collects on litter particles near the top of the litter bed. Once these exceed their storage capacity water begins to trickle deeper into the litter bed and once the litter bed exceeds its total storage capacity water is then lost to the soil or as runoff. Two approaches to modelling precipitation in litter beds have been suggested: a series of cascading buckets (Bristow *et al.* 1986) or as unsaturated flow in a porous medium (Kosugi *et al.* 2001), similar to the approach used in soil models. Both methods produce similar results. Although model parameters for *Eucalyptus* litter beds have not been measured, laboratory measurements of water retention of litter beds by Putuhena and Cordery (1996) may be useful in constructing a model.

2.3 Absorption of liquid water

When water is present on the surface of a fuel particle it will be absorbed until the litter reaches saturation. Although empirical FMC models implicitly treat absorption of water, very little work has been done to examine this physical process. Simard (1968) examined the wetting of some North American forest fuels. All fuels underwent a very rapid wetting during the first few hours of his experiments, followed by a gradual approach to saturation over a period of days. Saturation moisture contents were between 150 and 400% of dry weight. While further investigation of *Eucalyptus* fuels is required, preliminary measurements suggest saturation moisture contents of 200 and 250%.

2.4 Solar and thermal radiation

Solar radiation is the main source of energy for heating and drying of litter beds. Incoming solar radiation is absorbed and scattered by individual litter particles. Taken as an area average, the effect of leaves in the litter bed is to produce a profile of decreasing net solar radiation, i.e. the greatest energy input is at the top of the litter layer. Although specific models for solar radiation in litter beds have not been proposed, generic canopy radiation models have been adapted for use in agricultural mulch layers (Bristow *et al.* 1986; Bussiere and Cellier 1994; Novak *et al.* 2000) and this approach will be adapted for forest litter.

The sky, forest canopy, soil, and litter particles all emit and absorb thermal radiation. Because the emissivity of vegetation is close to 1 scattering is usually ignored in canopy thermal radiation models (Novak *et al.* 2000). Litter specific models of thermal radiation have been developed as a component of fire spread models (e.g. Vaz *et al.* 2004).

2.5 Heat and water vapour fluxes

Radiative heating and cooling of the litter elements results in temperature gradients between litter particles and the surrounding air, and between air at different levels in the litter bed. These gradients drive heat fluxes between the litter particles and air, and between all levels in the litter bed and the near-surface airflow.

Similarly, differences in vapour pressure between the surfaces of litter particles and surrounding air (usually expressed in FMC modelling as differences between FMC and EMC) or between the surface of intercepted precipitation and the surrounding air drive water vapour fluxes. If the vapour flux is towards the litter particles, then dew will form (Viney and Hatton 1990). Also, gradients in vapour pressure within the litter bed air spaces drive water vapour fluxes.

Fluxes between litter particles and air spaces, termed 'boundary layer fluxes' may be expressed as $Flux = K(X_{litter} - X_{air})$, where X is air temperature or vapour pressure and K is the boundary layer conductance. Monteith (1973) suggests formulae for K that should be suitable for application to forest litter. Boundary layer fluxes of heat and water vapour are also present at the soil surface and may be described using a similar formula Campbell (1985).

Representation of fluxes within airspaces is more challenging. Traditionally, a turbulent diffusion equation of the form $Flux = K dX/dz$ is used, where X is air temperature or vapour pressure and K is a conductance, usually dependent on wind speed. This method of modelling fluxes is known as the 'local flux-gradient' method, or 'K-theory'. Application of K-theory requires that the turbulent motions in the system are much smaller than the scale of the gradient in X. Studies indicate that turbulent motions in forest canopies (Raupach 1987) and mulch (Chen *et al.* 1997) are of similar scale to the canopy and hence that K-theory may fail in canopy airflows, of which a litter bed is an example. A more correct theory has been developed (Raupach 1987) but practical methods of application are still under development (van den Hurk and McNaughton 1995). The new fuel moisture model will initially attempt to apply K-theory using laboratory measurements of litter bed conductance but may adopt the method of van den Hurk and McNaughton (1995) if required.

Heat and vapour fluxes together play an important role in determining the local environment of the fuel particles and hence are an important determinant of fuel wetting and drying rates and moisture content. Empirical models to predict fuel level temperature and humidity from screen level measurements have been presented by Byram and Jemison (1943), van Wagner (1969), and Nelson (1991).

2.6 Heat conduction

In addition to radiative and turbulent fluxes of heat, conduction through the litter particles is also expected in the presence of temperature gradients. Riha *et al.* (1980) measured the conductance of forest litter and their values have been used in a mulch

model (Bussiere and Cellier 1994). Sensitivity studies have not been conducted so it is unclear whether heat conduction is a significant process in a sparsely packed forest litter layer.

2.7 Capillary flow

A capillary-flow water flux from the soil to the litter layer may be expected when the soil is sufficiently wet and the litter is not saturated (Schaap *et al.* 1997). However, this process has frequently been neglected in models because litter layers have been assumed to be too sparse to sustain significant capillary flow (Ogee and Brunet 2002). Laboratory measurements indicate that capillary rise does occur in *E. globulus* litter layers at very high soil moisture content but not at lower moisture contents.

2.8 Elevated and near-surface fuels

All the above processes, except capillary flow, also govern the moisture content of suspended fuels. The main differences between surface and near-surface and elevated fuel layers are that the latter have lower rainfall holding capacity, due to the sparse nature of these layers, and that the soil does not play a part in determining the heat and water vapour fluxes from the fuel.

3. Modelling the litter bed

The new fuel moisture model will predict the fuel moisture content of the litter bed and suspended fuel. The state of the fuel can be described by budget equations for five quantities:

- Intercepted precipitation,
- Fuel moisture content,
- Fuel temperature,
- Air temperature,
- Air humidity.

These equations describe changes in these five variables in terms of the processes described in Section 2. Processes may be modelled empirically or physically. Once the budget equations are determined and boundary conditions specified, FMC may be predicted by numerically integrating the equations forward in time.

There is considerable spatial variability in FMC, even at scales of just a few metres. The model will deal with this variability by assuming that although there is spatial variability in moisture content there are no horizontal fluxes. This allows the construction of a model with a single spatial dimension, height. Multiple copies of the model can then be used to represent spatial variability.

4. Applying the model

A model as described above requires specific boundary conditions to run: screen level meteorology, soil moisture, and soil temperature. Values of these conditions are required at frequent intervals, typically every 10 minutes. These values are not usually available for operational forecasting of FMC. Finding ways to approximate these values presents the main challenge when applying the model.

Fire weather observations and forecasts are usually limited to minimum and maximum temperatures, dew point, maximum wind speed, and daily rainfall. In some cases a nearby weather station may give more frequent observations. It is possible to

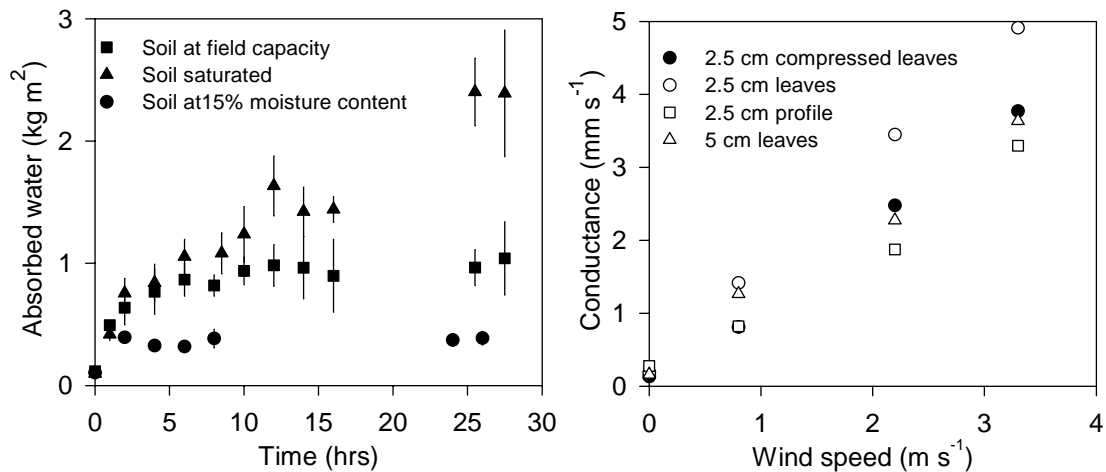


Figure 1, Laboratory studies. Left, water absorbed by a 1 cm thick *E. globulus* litter layer spread on soil. Vertical bars are 1 standard deviation. Right, water vapour conductance of leaf and profile litter layers.

interpolate between these sparse measurements by assuming that diurnal curves follow a typical pattern (e.g. Beck and Trevitt 1989). This approach will initially be tested for the new model.

A more sophisticated approach is to couple the fuel moisture model to a weather forecast model. This approach would remove the need for interpolation of measurements, as weather forecast models operate at similar resolution to the moisture model. Coupling the two models is not a trivial task. The simplest approach is using values from the forecast model's lowest atmospheric layer and top soil layer as boundary conditions for the moisture model. A more advanced approach would be to include the moisture model in a modified surface layer scheme for the weather forecast model.

An entirely different approach is to use the model to build tools that do not rely on book-keeping calculations. One possibility is a system to predict the number of days until a wet fuel bed is available for burning (N.P. Cheney, *pers. comm.*). The numerical model would be used to simulate drying curves for a wet fuel bed under different meteorological and site conditions. Statistically derived relationships between weather conditions, site characteristics and drying rates could then be packaged as a slide rule or set of tables.

5. Progress to date

Work on development of the new model has initially focused on laboratory measurements of model parameters and field observations which will be used to validate the model. Two sets of laboratory measurements have been made, the first to examine capillary flow in *Eucalyptus* litter beds, the second to measure the water vapour conductance of litter layers. Field observations have been made to provide detailed measurements of litter micrometeorology in conjunction with fuel moisture.

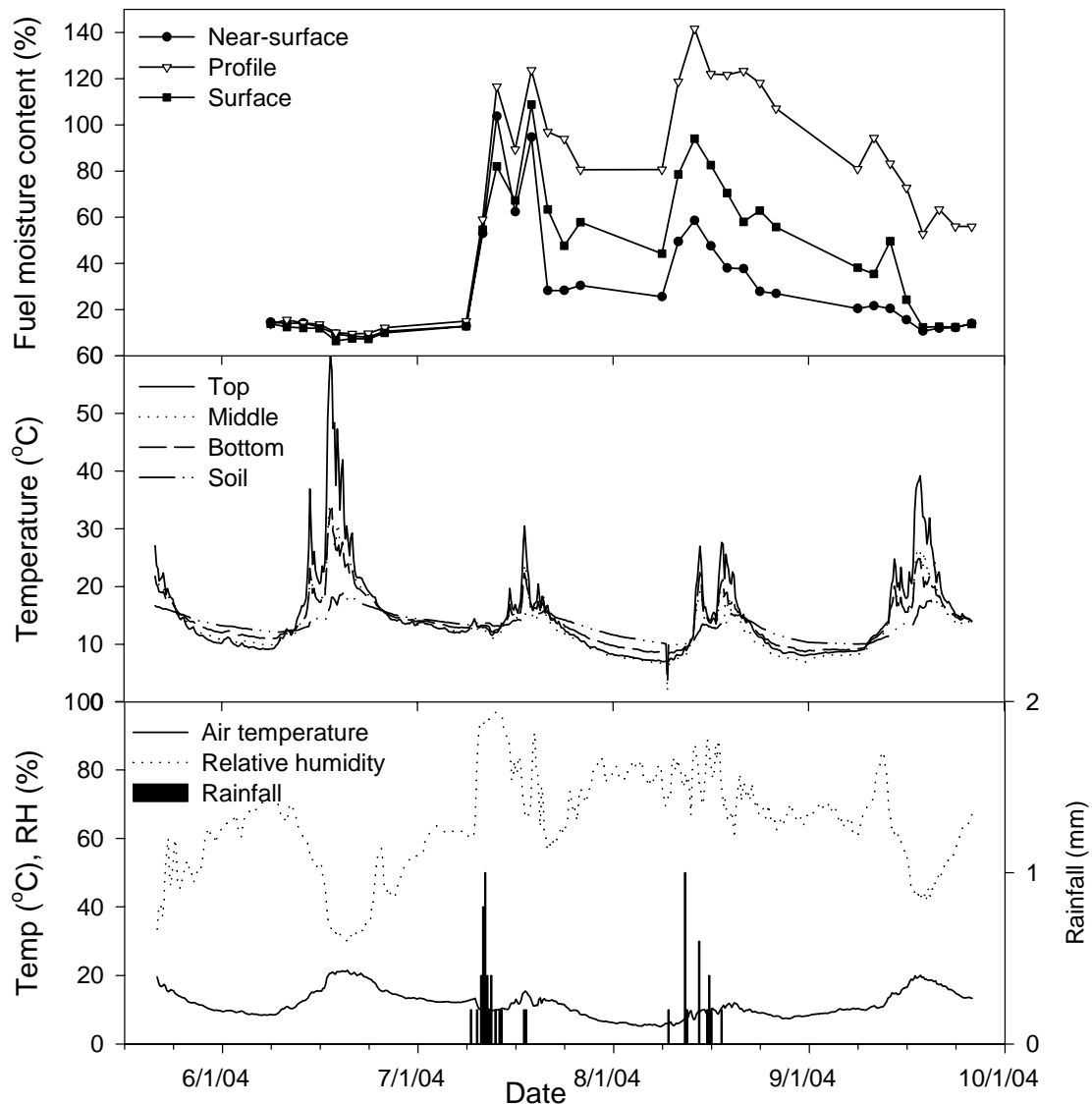


Figure 2: Field measurements from Mt Wellington, Tasmania. The experiment was held in an area of *E. obliqua* dominant forest with 20 t ha^{-1} fuel load. Top, surface, profile, and near-surface fuel moisture content. Middle, leaf temperatures at the top, middle, and bottom of the litter layer, soil temperature at 1 cm depth. Bottom, screen level weather conditions. Rainfall measurements are courtesy of Forestry Tasmania.

Capillary flow (Section 2.7) was examined by destructively sampling partially decomposed litter from *E. globulus* dominant mixed forest spread on soil samples with moisture contents of 15%, field capacity, and saturation. The results indicate that capillary flow does occur (Figure 1) and the total amount of water absorbed depends on the soil moisture content.

Litter layer conductance describes the rate at which heat and water vapour diffuse through the litter bed in response to gradients in air temperature and vapour pressure. Values of conductance of a litter layer are needed to describe turbulent heat and water vapour fluxes (Section 2.5). The water vapour conductance of leaf layers and partially decomposed litter layers was measured in the laboratory. Conductance was

calculated from measurements of evaporation from a water source covered by litter. Conductance increased with wind speed and showed only a weak dependence on litter layer type and thickness (Figure 1).

To provide data for model validation two periods of intensive field sampling have been conducted over four days at Mt Wellington, Tasmania and near Tumbarumba, NSW. Measurements included screen level meteorology, temperature profiles in the litter bed, and destructive samples of fuel moisture. The results from Mt Wellington (Figure 2) showed large differences in wetting of fuel during rainfall. Surface and near-surface fuels dried at similar rates, while profile fuel dried more slowly.

6. Summary

CSIRO Forestry and Forest Products is developing a new process based model of fine fuel moisture. This new model will predict moisture content by modelling the physical processes that determine fuel moisture: vapour exchange, rainfall interception, absorption of liquid water, radiation in the litter bed, turbulent fluxes of heat and water vapour, heat conduction, and capillary flow. These processes will be represented by budget equations for intercepted precipitation, fuel moisture content, fuel temperature, air temperature and humidity, which form the core of the model. Applying this type of process based model requires more frequent weather observations than are typically available in fire weather forecasts, and some strategies for synthesising suitable values have been identified. Work to date has focused on laboratory studies to determine model parameters and field work to obtain measurements for model validation.

7. References

- Anderson, H.E. (1990a) Moisture diffusivity and response time in fine forest fuels. *Canadian Journal of Forest Research* 20, 315-325.
- Anderson, H.E. (1990b) Predicting equilibrium moisture content of some foliar forest litter in the northern Rocky Mountains. USDA For. Serv., Res. Pap. INT-429, Intermt. Res. Stn., Ogden, UT, 10pp.
- Anderson, H.E., Schuette, R.D. and Mutch, R.W. (1978) Timelag and equilibrium moisture content of ponderosa pine needles. USDA For. Serv., Res. Pap. INT-202, Intermt. Res. Stn., Ogden, UT, 28pp.
- Beck, J.A. and Trevitt, A.C.F. (1989) Forecasting diurnal variations in meteorological parameters for predicting fire behaviour. *Canadian Journal of Forest Research* 19, 791-797.
- Bristow, K.L., Campbell, G.S., Papendick, R.I. and Elliott, L.F. (1986) Simulation of heat and moisture transfer through a surface residue-soil system. *Agricultural and Forest Meteorology* 36, 193-214.
- Bussiere, F. and Cellier, P. (1994) Modification of the soil temperature and water content regimes by a crop residue mulch: experiment and modelling. *Agricultural and Forest Meteorology* 68, 1-28.
- Byram, G.M. (1963) An analysis of the drying process in forest fuel material. Presentation at Int. Symp. on Humidity and Moisture, Washington, DC, 38pp.

Byram, G.M. and Jemison, G.M. (1943) Solar radiation and forest fuel moisture. *Journal of Agricultural Research* 67, 149-176.

Campbell, G.S. (1985) *Soil physics with BASIC*, Elsevier, Amsterdam, 150pp.

Catchpole, E.A., Catchpole, W.R., Viney, N.R., McCaw, W.L. and Marsden-Smedley, J.B. (2001) Estimating Fuel Response Time and Predicting Fuel Moisture Content From Field Data. *International Journal of Wildland Fire* 10, 215-222.

Chen, W., Novak, M.D., Black, T.A. and Lee, X. (1997) Coherent eddies and temperature structure functions for three contrasting surfaces, part I : ramp model with finite microfront time. *Boundary-Layer Meteorology* 84, 99-123.

King, A.R. and Linton, M. (1963a) Moisture variation in forest fuels: the rate of response to climate changes. *Australian Journal of Applied Science* 14, 38-50.

King, A.R. and Linton, M. (1963b) Report on moisture variation in forest fuels: equilibrium moisture content. CSIRO Div. Phys. Chem. Rep., Melbourne, Australia, 9pp.

Kosugi, K., Mori, K. and Yasuda, H. (2001) An inverse modeling approach for the characterisation of unsaturated water flow in an organic forest floor. *Journal of Hydrology* 246, 96-108.

McArthur, A.G. (1967) Fire Behaviour in Eucalypt forests, Leaflet No. 107, Canberra: Forestry and Timber Bureau.

Monteith, J.L. (1973) *Principles of environmental physics*, Edward Arnold Ltd., London, 241pp.

Nelson, R.M. (1991) A model of diurnal moisture change in dead forest fuels, 11th conference on fire and forest meteorology, Missoula, MT, 109-116.

Nelson, R.M.. (2000) Prediction of diurnal change in 10-h fuel stick moisture content. *Canadian Journal of Forest Research* 30, 1071-1087.

Novak, M.D., Chen, W.J. and Hares, M.A. (2000) Simulating the radiation distribution within a barley-straw mulch. *Agricultural and Forest Meteorology* 102, 173-186.

Ogee, J. and Brunet, Y. (2002) A forest floor model for heat and moisture including a litter layer. *Journal of Hydrology* 255, 212-233.

Pitman, A.J. (2003) The evolutions of, and revolution in, land surface schemes designed for climate models. *International Journal of Climatology* 23, 479-510.

Putuhena, W.M. and Cordery, I. (1996) Estimation of interception capacity of the forest floor. *Journal of Hydrology* 180, 283-299.

Raupach, M.R. (1987) A lagrangian analysis of scalar transfer in vegetation canopies. *Quarterly Journal of the Royal Meteorological Society* 113, 107-120.

Riha, S.J., McInnes, K.J., Childs, S.W. and Campbell, G.S. (1980) A finite element calculation for determining thermal conductivity. *Soil Science Society of America Journal* 44, 1323-1325.

Schaap, M.G., Bouten, W. and Verstraten, J.M. (1997) Forest floor water content dynamics in a Douglas fir stand. *Journal of Hydrology* 201, 367-383.

Simard, A.J. (1968) The moisture content of forest fuels - II Comparison of moisture content variations above the fibre saturation point between a number of fuels. Can. Dept. of For. And Rural Dev., For. Fire Res. Inst., Inf. Rep. FF-X-15, Ottawa, Ont, 68pp.

Sneeuwjagt, R.J. and Peet, G.B. (1998) *Forest fire behaviour tables for Western Australia*, Dept. of Conservation and Land Management, Perth, Australia, 59pp.

van den Hurk, B.J.J.M. and McNaughton, K.G. (1995) Implementation of near-field dispersion in a simple two-layer surface resistance model. *Journal of Hydrology* 166, 293-311.

van Wagner, C.E. (1969) Combined effects of sun and wind on surface temperature of litter . Petawa for. exp. station, Chalk river, Ontario, Inf. Rep. PS-X-10, 8pp.

van Wagner, C.E. (1972) Equilibrium moisture content of some fine fuels in eastern Canada . Petawa for. exp. station, Chalk river, Ontario, Inf. Rep. PS-X-36, 12pp.

van Wagner, C.E. (1979) A laboratory study of weather effects on the drying rate of jack pine litter. *Canadian Journal of Forest Research* 9, 267-275.

van Wagner, C.E. (1987) Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forest Service Technical Report No. 35, 37pp.

Vaz, G.C., Andre, J.C.S. and Viegas, D.X. (2004) Estimation of the radiation extinction coefficient of natural fuel beds. *International Journal of Wildland Fire* 13, 65-71.

Viney, N.R. (1991) A review of fine fuel moisture modelling. *International Journal of Wildland Fire* 1, 215-234.

Viney, N.R. and Hatton, T.J. (1990) Modelling the effect of condensation on the moisture content of forest litter. *Agricultural and Forest Meteorology* 51, 51-62.

Walsh, R.P.D. and Voigt, P.J. (1977) Vegetation litter: an underestimated variable in hydrology and geomorphology. *Journal of Biogeography* 4, 253-274.