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Review

Dead fuel moisture research: 1991–2012

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Abstract. The moisture content of dead fuels is an important determinant of many aspects of bushfire behaviour. Understanding the relationships of fuel moisture with weather, fuels and topography is useful for fire managers and models of fuel moisture are an integral component of fire behaviour models. This paper reviews research into dead fuel moisture for the period 1991–2012. The first half of the paper deals with experimental investigation of fuel moisture including an overview of the physical processes that affect fuel moisture, laboratory measurements used to quantify these processes, and field measurements of the dependence of fuel moisture on weather, vegetation structure and topography. The second set of topics examine models of fuel moisture including empirical models derived from field measurements, process-based models of vapour exchange and fuel energy and water balance, and experimental testing of both types of models. Remaining knowledge gaps and future research problems are also discussed. Opportunities for exciting research in the future exist for basic fuel moisture processes, developing new methods for applying models to fire behaviour prediction, and linking fuel moisture and weather forecast models.

Additional keywords: forest litter, fuel moisture content, model, review.

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Introduction

Fuels consumed in wildland fire are a mix of live and dead plant material, the water content of which plays an important role in determining fire behaviour (Rothermel 1983). Because the removal of water requires energy, fuel moisture content (FMC) – defined as the mass of water per unit mass of dry material – partially determines the effective heat released when fuel burns. This in turn determines fire attributes such as rate of spread, flame dimensions and fuel consumption (McArthur 1967; Rothermel 1983). Knowledge of FMC is thus required to predict fire behaviour, and almost all fire models include dead FMC as an input variable.

FMC may be measured by a variety of means, the most common being oven drying (Matthews 2010) or measurement of the electrical resistance of fuel (Chatto and Tolhurst 1997). It is not always possible to make timely measurements of FMC, because oven drying takes 24 h and even instantaneous methods cannot be used for predictions, so models are used to predict FMC. There are two main approaches to predicting FMC: empirical or process-based models. An empirical model uses statistics to construct relationships between FMC and input variables (weather, fuel and site characteristics) from field observations. The forms of the equations and choice of variables may be guided by understanding of physical processes but in-depth understanding is not required. Process-based models predict FMC by attempting to simulate the processes that occur in the fuel. These models are constructed from theoretical understanding, laboratory and field experiments.

This paper reviews dead FMC research since the publication of the first review of dead fine FMC by Viney in 1991. All models that were in operational use at the time were included, as well as some models that had been used only for research. Ruiz Gonzalez and Vega Hidalgo (2007) extended Viney's work by including an overview of FMC processes and methods for measuring FMC. They present a detailed exploration of the models covered in Viney (1991), including updates to models (e.g. Lawson *et al.* 1996) and also some coarse FMC models. These two papers are the starting point for the present review, which does not include any of the models reviewed by either paper. Drought indices are not considered here as they have been recently reviewed by Heim (2002) and Zargar *et al.* (2011). To limit the scope of this review, live FMC (Chuvieco *et al.* 2002) and remote sensing of weather variables (Nieto *et al.* 2010) have not been included. Although the focus of this paper is FMC as it pertains to fire behaviour, litter water dynamics are also relevant to forest hydrology (Ogée and Brunet 2002) and atmospheric fluxes (Haverd and Cuntz 2010). It is hoped that this paper may also be useful to workers in those fields.

The paper is divided into five sections. The first provides an overview of the processes that determine FMC, with an emphasis on experimental measurements. The second covers field measurements that have examined the effects of topography, vegetation and fuel structure on FMC. The third and fourth sections review empirical and process-based models. The fifth section examines studies that have applied existing models to field measurements, for either model validation or adaptation.

Fuel moisture physics and laboratory measurements

Dead fuel is separated into fine fuels – leaves, bark and twigs less than 6 mm in diameter – and coarse fuels – larger twigs, fallen limbs and logs. In the nomenclature of the US National Fire Danger Rating System (Burgan 1988) the 1-h fuel class is fine fuel and the 10-, 100- and 1000-h classes are coarse fuels. Fine FMC is usually considered a single value, so variation inside the fuel is not considered, whereas for coarse fuel it may be necessary to consider FMC variation within the fuel. It is also common to distinguish between the FMC of the surface, profile and duff layers of the litter bed, and fuels suspended above the ground (Gould *et al.* 2011).

FMC responds to changes in temperature and relative humidity and the presence of water on the fuel surface. These in turn depend on radiation, precipitation, and heat and water vapour fluxes. Processes directly affecting the individual fuel elements have received the most attention in prior work, with much less attention paid to litter bed processes (Viney 1991).

Vapour exchange

Vapour exchange occurs when the vapour pressure at the surface of the fuel differs from that of the surrounding air (Viney 1991). Two processes occur during vapour exchange (Byram 1963): exchange of water across the surface of the fuel and diffusion within the fuel. Byram (1963) assumed that vapour exchange was governed by internal diffusion, with FMC at the surface of the fuel adjusting instantaneously so that the pressure difference with the atmosphere was zero. This zero gradient moisture content is called the equilibrium moisture content (EMC). Vapour exchange can be described with a differential equation:

$$\frac{dm}{dt} = \frac{m_e - m}{\tau} \quad (1)$$

where m is FMC, m_e is EMC and τ is the response time (h), a parameter that governs the rate at which FMC approaches EMC. EMC curves have a sigmoid shape as a function of relative humidity (Fig. 1) but also depend on temperature and whether EMC is approached by adsorption or desorption. The difference between adsorption and desorption curves is an example of hysteresis. The most commonly used model is that of Nelson (1984):

$$m_e = a + b \ln\left(\frac{-RT}{M} \ln\left(\frac{H}{100}\right)\right) \quad (2)$$

where $R = 1.987\ \mathrm{cal\,mol^{-1}\,K^{-1}}$ is the universal gas constant, $M = 18.015\ \mathrm{g\,mol^{-1}}$ is the molar mass of water, T (K) is air temperature and H (%) is relative humidity. This has been used successfully in several models (Nelson 2000; Catchpole *et al.* 2001; Matthews 2006) but may cause problems at very high or low humidity as predicted EMC tends to infinity. Byram (1963) showed that changes in FMC due to vapour exchange could be represented as:

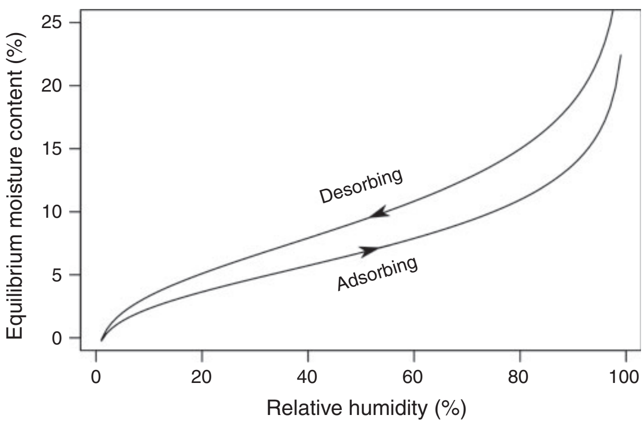

Fig. 1. Equilibrium moisture content (EMC) curves for a typical dead fuel calculated using the Nelson (1984) model. EMC depends on air temperature, relative humidity and whether the fuel is losing (desorption) or gaining (adsorption) moisture.

$$m_{(t)} = m_e + (m_{(0)} - m_e)e^{\frac{-t}{\tau}} \quad (3)$$

where $m_{(t)}$ is the FMC (% or $\mathrm{kg\,kg^{-1}}$) at time t. The fuel is characterised by its EMC (a function of T and H) and response time. Equation 3 has been used in several models (Fosberg 1971; Fosberg and Deeming 1971; Fosberg *et al.* 1981; van Wagner 1987; Nelson 1991; Catchpole *et al.* 2001; Fiorucci *et al.* 2008; Qu *et al.* 2010*a*). Hysteresis has been neglected in most models but this has not had a measurable effect on model performance, either because errors in field measurements are too large to reveal hysteresis, or because when fitting response time and EMC, hysteresis is absorbed into the response time (Catchpole *et al.* 2001). EMC and response times have been measured for North American (Blackmarr 1971; van Wagner 1972; Britton *et al.* 1973; Anderson *et al.* 1978; van Wagner 1979; Anderson 1990*a*, 1990*c*; Hille and den Ouden 2005), European (Schunk *et al.* 2013) and Australian species (King and Linton 1963*a*, 1963*b*; Pippen 2008; Cruz *et al.* 2010).

Precipitation

Forest litter can store large quantities of precipitation (Walsh and Voigt 1977). Water initially collects on litter elements near the top of the litter bed. Once these exceed their storage capacity water begins to trickle deeper into the litter and is then lost to the soil or as runoff. Two approaches to modelling precipitation in litter have been suggested: cascading buckets (Bristow *et al.* 1986) or as unsaturated flow in a porous medium (Kosugi *et al.* 2001). Both methods produce similar results.

Retention of water by *Eucalyptus* spp. and *Pinus radiata* (D. Don) beds was measured in the laboratory by Putuhena and Cordery (1996). They found that eucalypt litter retained up to 113% of dry mass and pine fuel, 96%. Later experiments with broadleaf species by Sato *et al.* (2004) showed the water retention depends on rainfall rate, with retention at rainfall of

5 mm h^{-1} being half that at 50 mm h^{-1}. Retention varied from 50 to 150% of dry mass. Guevara-Escobar *et al.* (2007) investigated the interception capacity of poplar (*Populus nigra* L.), grass (*Aristida divaricata* Humb. and Bonpl. ex Willd.) and woodchips (*Pinus* sp.). They found that peak storage increased with rainfall but that retention after drainage had stopped did not increase with rainfall intensity, in contrast to Sato's results. Retention for poplar litter was 150% of dry mass.

Using a lysimeter (Gerrits *et al.* 2007), Gerrits *et al.* (2010) measured rainfall interception in a beech (*Fagus sylvatica* L.) forest. Litter water storage was on average 1.8 mm but peaked at 2.8 mm during autumn when new leaves were deposited on the forest floor. Leaf shapes had an effect on storage capacity, with higher storage in curly, freshly dropped leaves than in leaves that had been flattened under snow.

Precipitation also forms as dew when radiative cooling lowers the temperature of the litter below the dew point. Field measurements of reindeer lichen (*Cladina rangiferina* (L.) Nyl.) FMC by Péch (1991) showed a linear relationship between dew amount and increase in FMC. Viney and Hatton (1990) demonstrated that dew could be predicted using an energy balance model and that omitting dew formation led to significant underprediction of morning FMC.

Absorption of liquid water

When water is present on the surface of fuel it will be absorbed until the fuel reaches saturation. Simard (1968) examined the wetting of some North American forest fuels and found that all fuels underwent a very rapid wetting during the first few hours, followed by a gradual approach to saturation over a period of days. Saturation moisture contents were between 150 and 400%. Measurements of eucalypt fuels have found values of between 110 and 160% (Matthews 2006; Pippen 2008).

Radiation

Solar radiation is a source of energy for heating and drying fuels. The effect of layering of fuel in litter is to produce a profile of exponentially 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 have not been proposed, canopy radiation models have been adapted for use in mulch layers (Bristow *et al.* 1986; Bussiere and Cellier 1994; Novak *et al.* 2000) and this approach can be used for forest litter. Empirical models have also been developed (Byram and Jemison 1943; van Wagner 1969; Rothermel 1983) The forest canopy also reduces the amount of radiation reaching the fuels. Interception by the canopy is described using the Beer Law exponential decay model (Monteith and Unsworth 1990).

$$S = S_0 e^{-\gamma L} \tag{4}$$

where S (W m^{-2}) is solar radiation below the canopy, S_0 (W m^{-2}) is radiation above the canopy, γ is an attenuation coefficient and L is leaf area index.

The sky, forest canopy, soil and fuel all emit thermal radiation according to the Stefan–Boltzman law (Monteith and Unsworth 1990):

$$R = \varepsilon \sigma T^4 \tag{5}$$

where R is emitted radiation (W m^{-2}), ε is the emissivity of the material, $\sigma = 5.67 \times 10^{-8}$ J s^{-1} m^{-2} K^{-4} and T (K) is temperature. Litter specific models of thermal radiation have been developed as a component of fire spread models (Vaz *et al.* 2004) and mulch models may also be applied (Bristow *et al.* 1986; Bussiere and Cellier 1994; Novak *et al.* 2000).

Heat and water vapour fluxes

Heating and cooling of fuel results in temperature gradients between fuel and the surrounding air, and between air pockets at different depths in litter. These gradients drive heat fluxes between the fuel and air, and between all levels in litter and the near-surface airflow. Similarly, differences in vapour pressure between fuels and surrounding air drive water vapour fluxes.

Fluxes between fuel and air are expressed as $F_x = K(X_{litter} - X_{air})$, where F_x is the flux, X is temperature or vapour pressure and K is the boundary layer conductance. Monteith and Unsworth (1990) suggest formulae for K that are suitable for forest fuels. Fluxes of heat and water vapour are also present at the soil surface and are described similarly Campbell (1985).

Modelling fluxes within airspaces is more challenging. Traditionally, a turbulent diffusion equation is used:

$$F = K \frac{dX}{dz}$$

where K is conductance, usually dependent on wind speed, and dz is a vertical increment. Application of this equation requires that turbulent motions in the system be much smaller than the scale of the gradient in X. Because turbulence scales in forest canopies (Raupach 1987) and mulch (Chen *et al.* 1997) are similar to that of the canopy, this theory may fail in litter layers. A better theory has been developed (Raupach 1987; Van den Hurk and McNaughton 1995) but has not yet been applied to FMC models.

Measurements of water vapour fluxes through eucalypt litter were reported by Matthews (2005), who found that conductance decreased with litter depth and bulk density, and was lower in the bottom half of the profile. Schaap and Bouten (1997) measured bulk evaporation from the litter bed in a pine forest and found that resistance to evaporation decreased linearly with FMC. Nelson and Hiers (2008) found that for horizontally oriented litter beds, response time increased with fuel load – from a range of 3.3–5.3 h for individual needles, to 31.6 h for 1-kg m^{-2} loading (41 mm-deep layer). For vertically oriented needles there was a slower increase, with a response time of 8.6 h for a 1-kg m^{-2} fuel load (360-mm depth).

Heat conduction

Conduction through the fuel occurs in the presence of temperature gradients. Riha *et al.* (1980) measured the conductance of forest litter and these values have been used in a mulch model (Bussiere and Cellier 1994). However, sensitivity studies were not conducted so it is unclear whether heat conduction is a significant process in a sparsely packed forest litter layer.

Absorption of soil water

A water flux from soil to litter may occur when the soil is sufficiently wet and the litter is not saturated (Schaap *et al.* 1997). This is driven by capillary action, the transport of water against gravity by intermolecular forces. This process has frequently been neglected in models because litter layers have been assumed to be too sparse to sustain a capillary flux (Ogée and Brunet 2002). Rothwell *et al.* (1991) and Samran *et al.* (1995) showed the exchange of water between soil and duff was a significant determinant of FMC in Aspen forests.

Movement of water in woody fuels

Coarse fuels are exposed to the same environmental conditions as are fine fuels but differ in that it is necessary to consider movement of water within the fuel. Water within coarse fuels is transported radially by either capillary flow or diffusion (Nelson 2000). The capillary flow mechanism is described by Nelson (2000):

> The wood cell that holds liquid water is a long tube with a roughly square cross-section and tapered ends. Flow between unsaturated cells is induced by capillary pressure differences, which depend on size of the cell cavities; it takes place through small orifices (bordered pits) located only on the overlapping tapered ends of the cells.

Capillary flow occurs only when there is enough water that the liquid is continuous between cells but does extend beyond their tapered ends, ~41–74% (Nelson 2000). Outside this range transport is by diffusion only. Moisture diffusion occurs by movement of water bound in cell walls and water vapour down moisture gradients, described by a diffusion equation. In addition to these processes, FMC in coarse fuels may be affected by bark, cracks in the fuel and decay.

Suspended fuels

All the above processes other than capillary flow affect the FMC of suspended fuels. The main differences between surface and suspended fuel layers are that the latter have lower rainfall holding capacity, due to their sparseness, and that the soil does not play a part in determining the heat and water vapour fluxes from the fuel. Because suspended fuel is less dense than litter fuels, it is rare that air temperature and humidity will vary markedly from screen height (1.2 m above ground) meteorological conditions (Cruz *et al.* 2010). This simplifies the problem of determining fuel level conditions as prediction of small scale fluxes is not required.

Field measurements

Field experiments have investigated the dependence of FMC on vegetation, topography or position in the landscape, and plant life cycle. They have also been used for model testing and development.

Where there are changes in vegetation structure there are commonly differences in FMC. Biddulph and Kellman (1998) compared FMC measurements between forest and treeless savannah. They found that forest fuels dried more slowly than savannah fuels, regardless of location, and that forest microclimate promoted slower drying than savannah microclimate. Along a transect near the forest edge savannah fuels were moister closer to the forest for 1 day after rain but this effect disappeared after 2 days and was reversed after 18 days. Ray *et al.* (2005) measured FMC and micrometeorology in mature, regrowth and logged forest stands. They found that canopy height and leaf area index had a significant effect on FMC, with taller, denser canopy resulting in slower drying after rain. Differences were driven by variation in below-canopy vapour pressure deficit. Initial moisture content after rainfall events varied only slightly with rainfall amount.

For forests with high canopy density (e.g. lodgepole pine, *Pinus contorta* Dougl.; white spruce *Picea glauca* (Moench.) Voss), interception of water by trees led to finescale variation in duff moisture content (Raaflaub and Valeo 2008), but this was not seen in trembling aspen (*Populus tremuloides* Michx) forest. Tanskanen *et al.* (2006) examined FMC in pine (*Pinus sylvestris* L.) stands ranging in age from 0 to 60 years and canopy cover from 7 to 74%. Fuels in younger, more open stands were consistently drier than those in older stands, and drying rates were higher in younger stands. This effect was due to differences in micrometeorology rather than canopy rainfall interception or fuel load. Glitzenstein *et al.* (2006) measured FMC in long unburnt pine (*Pinus taeda* L) forest over 2 days and found that litter, grass and 10-h fuels were drier in a chipped treatment that in the control treatment, but that 1-h woody fuels were wetter. In contrast, Faiella and Bailey (2007) found that burning and burn-and-thinning treatments in pine (*Pinus ponderosa* Lawson var. *scopulorum* Engelm) forest did not have any significant effect on fine or coarse FMC. Modification of forest structure can also affect micrometeorology and FMC. For example, Miller *et al.* (2007) found that clearings in tropical forests in Brazil acted as vents, allowing enhanced movement of water vapour out of undisturbed areas through advection. The effects of logging and land clearing on FMC in tropical forests were examined by Uhl and Kauffman (1990) and Holdsworth and Uhl (1997).Both studies found that removing or reducing canopy cover meant that fuel dried more rapidly after rain.

Marsden-Smedley and Catchpole (2001) measured FMC in buttongrass (*Gymnoschoenus sphaerocephalus*) moorlands of varying fuel cover and location but did not find any effect of cover on FMC. Pook (1993) and Pook and Gill (1993) examined variation in FMC in the field and inside an instrument screen for pine and eucalypt fuels, also including differences due to arrangement (litter *v.* suspended), forest structure (control *v.* thinned–pruned), fuel component (leaves, twigs, bark) and weathering. Although FMC in all treatments was highly correlated at FMC <20%, most factors had a significant effect on FMC. Of note, FMC was lower in thinned–pruned stands due to greater exposure to radiation, pine fuels lad lower FMC than eucalypt fuels, and suspended fuels were drier than litter fuels. Measurements in mallee–heath vegetation showed that the relationship between litter and suspended fuel depends on antecedent weather with suspended fuels drying more quickly after rain but litter fuels having lower FMC in dry conditions (Cruz *et al.* 2010).

Ferguson *et al.* (2002) used soil moisture probes to track the FMC of pine litter and duff. They found a significant effect of fuel bed depth on response to rainfall, with larger amounts of rain required to wet deeper fuel beds. In contrast, drying rates were independent of weather conditions, attributed to rapid drainage into underlying sandy soil. Samran *et al.* (1995) examined the contribution of soil water, rain and slope position to aspen surface FMC. They found that rainfall was dominant in the upper litter and soil water dominant in the bottom of the litter. The lower slope site was always the wettest, with no difference between the upper- and mid-slopes. Schaap *et al.* (1997) examined litter and duff FMC in a fir stand and found that FMC was spatially variable, depending on litter depth, but that FMC was closely correlated among samples. During and after rainfall, interception and drainage dominated FMC changes and evaporation rates were limited by seasonal water availability. Water uptake from soil by capillary action was a significant contributor to duff moisture whereas root uptake played only a minor role. Schaap *et al.* (1997) concluded that forest floor moisture dynamics were dominated by evaporation in dry periods and by interception and drainage during rain. Keith *et al.* (2010*a*) found that in the period 24–72 h after rainfall there was significant downslope movement of water through duff, particularly in forests with deeper duff. After this period, horizontal movement ceased and water budgets were again determined by local evaporation. Examination of diurnal cycles in duff water balance (Keith *et al.* 2010*b*) showed that moisture content was highest during the middle of the day, the opposite of what is observed for litter fuels. This cycle was driven by the relative balance of upward flux from the soil and evaporative demand from the atmosphere.

Stambaugh *et al.* (2007) measured FMC as a function of aspect under both wet and dry conditions in hardwood forests in the Ozark Highlands, in southern USA. During very wet and very dry conditions FMC was independent of aspect. During intermediate conditions FMC was highest on northerly aspects, lowest on southerly aspects and intermediate on both east and west aspects. Gibos (2010) compared FMC on north- and south-facing lodgepole pine forests in Canada. Although the south-facing sites were slightly warmer (1.5°C), had lower humidity (5%) and higher above-canopy radiation (20%) a significant difference in FMC was not measured. This was attributed to the dense forest canopy – which reduced differences in below canopy radiation to less than 1 W m^{-2} – and limits in the ability of measurements to resolve the 1–2% differences in FMC predicted using the FFMC model (van Wagner 1987).

Lopes *et al.* (2006) and Lopes *et al.* (2010) used several years of daily (summer) and weekly (autumn–spring) measurements in mixed eucalypt and pine forest in Portugal to examine seasonal cycles. Monthly average FMC was lowest (between 10–20%) in mid-summer, rising to 50% in winter, driven by seasonality of rainfall. Due to large variation within each month, significant differences between species were not observed. Measurements from three sites along an 8-km transect did not show any spatial variation.

Plant life cycle has been found to have an effect on FMC. Baeza *et al.* (2002) found that the dead fraction of gorse (*Ulex parviflorus* Pourr.) increased with age, whereas Kuljian and Varner (2010) found that the foliar FMC of disease-killed oak (*Lithocarpus densiflorus* (Hook. & Arn.) Rehd.) was similar to that of litter. Williams *et al.* (1998) examined seasonal variation in litter, grass and twig moisture in a tropical savannah. They found that litter and grass FMC were lower in the late dry season than in the early dry season. Recent bark beetle (*Dendroctonus ponderosae*) attacks on pine species in North America have produced forests with large amounts of suspended dead fuels following tree death. FMC of needles on dead trees has been measured in the range 6–32%, similar to suspended dead fuels in healthy trees (Jolly and Hadlow 2012; Page *et al.* 2012).

Derivation of new empirical models from measurements

The complexities of fuel moisture processes mean that implementing models that account for all these processes is very challenging. Consequently, development of empirical models has been a popular approach, used in operational FMC models (Ruiz Gonzalez and Vega Hidalgo 2007) and the more recently developed models described here.

In many studies, multiple linear regression against weather variables has been used:

$$m = a_0 + \sum_{i=1}^{n} a_i X_i \tag{6}$$

where a_i are empirical constants and X_i are weather variables. In some cases lagged rather than instantaneous weather is included but predictions for this form of model are always independent of previous FMC values. Table 1 summarises the models described below where this equation has been used. The models are presented in alphabetical order.

Alves et al. *(2009)*

Alves *et al.* (2009) measured FMC of pine (*Pinus elliottii* Engelm.) litter in Brazil for 32 h by repeated-measurement of litter baskets ($n = 240$) and by destructive sampling ($n = 84$). Relationships between FMC and weather were tested using exhaustive comparisons against air temperature (T), wind speed (U), and relative humidity (H). T and H were highly correlated ($R^2 > 0.9$) and the linear model selected included air temperature and wind speed as independent variables (Table 1). Although it is unusual for humidity not to appear in the model, this was likely due to the high correlation between T and H and the very short sampling period. Given that the measurements covered less than 2 days and FMC is predicted to increase with air temperature it is questionable whether this model could be widely applied.

Ferguson et al. *(2002)*

Ferguson *et al.* (2002) used continuous measurements from soil moisture probes made over 180 days in a Florida pine (*Pinus palustris*) forest to relate changes in pine litter and duff moisture content to antecedent weather conditions. They found that moisture values were strongly auto-correlated so that moisture index could be predicted from the previous day's index and rainfall:

$$I_t = 0.9957 I_{t-1} + 0.023\sqrt{r_t} - 0.013\sqrt{r_{t-1}} \tag{7}$$

where I_t is the moisture index on day t and r_t is 24-h rainfall on day t. Predictions and observations were well correlated with $R^2 > 0.9$. I was compared with measured FMC from weekly destructive sampling over the experimental period with R^2 from 0.13 to 0.56

Table 1. Coefficients for models that are linear functions of weather variables

Reference	Predicted variable	Constant	Air temperature (°C)	Minimum air temperature (°C)	Surface temperature (°C)	Dew point temperature (°C)	Relative humidity (%)	2-h-lagged relative humidity (%)	Previous day's minimum relative humidity (%)	Wind speed ($m s^{-1}$)	Soil moisture content (% vol)	Leaf area index	Vapour pressure deficit (kPa)	Inverse of days since rain (day^{-1})
Alves *et al.* (2009)	$m_{surface}$	1.59	0.09							−20.0				
Lin (2004)	$m_{surface, site 1}$	Not given	−0.84				0.53							
	$m_{surface, site 2}$	Not given	−1.1				0.4							
Marsden-Smedley and Catchpole (2001)	$\log(m_{suspended})$	1.66				0.03	0.02							
Pook and Gill (1993)	$m_{suspended}$	8.56	−0.18				0.18							
	$m_{stevenson screen}$	9.11	−0.14				0.14							
	$m_{surface}$	9.67	−0.27				0.27							
	$m_{surface}$	8.1	−0.13				0.13				0.069			
Ray *et al.* (2010)	$m_{profile}$	977										0.371	−0.68	1.36
Ruiz González *et al.* (2009*a*)	$m_{stevenson screen}$	1.72		0.12			0.04	0.09	0.07					
Sharples *et al.* (2009)	Moisture index, F	10	−0.25				0.25							
Zhang *et al.* (2006)	$m_{surface}$	42.3	−1.011		−0.98		0.74							

Lin (2004)

Lin (2004) measured pine (*Pinus taiwanensis*) litter FMC by destructive sampling in two locations in Taiwan. Litter was collected hourly from 0800 to 1600 hours for 5–7-day periods throughout several fire seasons for a total of 85 and 90 sampling days at each site. After exclusion of observations where FMC was >25% multiple linear regression was performed against T, H, U and cloud cover (C). For both sites T and H were selected as predictor variables (Table 1) and R^2 for the models was 0.53 and 0.60.

Marsden-Smedley and Catchpole (2001)

Marsden-Smedley and Catchpole (2001) measured FMC in buttongrass moorlands in Tasmania, Australia. The majority of dead fuel was suspended in the buttongrass clumps so litter fuels were not sampled. Destructive sampling of suspended fuel was performed during daylight hours for 3–6-day periods between rain events during the spring, summer and autumn of 1992. Two models were fit to the data, the first being a linear model using relative humidity and dew point temperature (T_{dew}) to predict log-transformed FMC (Table 1). H and T_{dew} were selected because these were uncorrelated, whereas the commonly used combinations of T and H or T and T_{dew} were both correlated. A statistically significant seasonal effect was observed but accounted for less than 4% of variation. Model parameters for adsorbing and desorbing conditions were not significantly different. Parameters were also fit for the Catchpole *et al.* (2001) model.

Pook and Gill (1993)

Pook (1993) and Pook and Gill (1993) measured the moisture content of pine (*Pinus radiata*) litter, duff and suspended fuels in plantations in Canberra, Australia, during the fire seasons of 1988–89, 1990–91 and 1991–92. FMC was measured destructively at 1400–1500 hours on days at least 24 h after the most recent rainfall in mature thinned–pruned and unthinned–unpruned stands. Measurements were also made 3 hourly on 15 days in 1990–91 and 1991–92. In 1989–90 bunches of suspended fuel were exposed in a shaded, louvered box and weighed repeatedly between dawn and midnight for several days.

Multiple linear regression was performed using the 1988–89 and 1990–91 data for a range of subsets of T, H, duff moisture content and soil moisture content with models ranked by R^2 (Pook and Gill 1993). Pook (1993) refined these to two models based on $(T-H)$ for suspended fuels, and models based on $(T-H)$ and $(T-H)$ plus soil moisture for litter (Table 1). Inclusion of soil moisture in the litter models improved performance, and the two suspended fuel models performed similarly.

Ray et al. *(2010)*

Ray *et al.* (2010) used measurements of forest litter in the Brazilian Amazon to develop a model of profile FMC. Baskets of litter at four sites were sheltered under a plastic roof, exposed to artificial rainfall events and then repeatedly weighed 2 hourly from 0800 to 1600 hours for up to 9 days. Multiple linear regression was conducted against forest Leaf Area Index (LAI), vapour pressure deficit (VPD) and a variety of measures of rainfall: amount (mm), time since rain (d), inverse time since rain (day^{-1}) and the ratio of rainfall amount to time since rain (mm day^{-1}). Selected variables were LAI, VPD and inverse time (Table 1). Rainfall amount was not selected because initial fuel wetting was independent of rainfall amount. The model was tested against destructive samples collected weekly from August to December 2003 at 4 sites. Predictions were unbiased but scattered for FMC <50%, under-predicted at higher FMC and the model was able to predict whether FMC was below 50% for approximately half of the samples.

Ruiz González et al. *(2009*a*)*

Following Pook (1993), Ruiz González *et al.* (2009*a*) constructed two models for the FMC on pine needles and twigs. Samples from six sites in Spain were collected from pine (*Pinus pinaster* and *P. radiata*) forests and exposed to ambient weather conditions in Stevenson screens for 4–15 days in the summers of 2001 and 2002. FMC was determined by repeated weighing of samples every 2–4 h during daylight hours. Multiple linear regression was used to construct two models. The first used the same parameters for all samples and the second used different parameters for different species, fuel type (litter needle, litter twig, suspended needle, suspended twig, needles attached to branches) and sorption direction. Variables selected were H at the time of measurement, H 2 h before measurement, and the minimum temperature and maximum H of the preceding day (Table 1). Both models performed well but the authors suggest that the small improvement offered by using the second model did not justify the additional complexity.

Sharples et al. *(2009)*

Sharples *et al.* (2009) proposed ($T-H$) (Pook 1993) as a variable that could be used to predict FMC across a variety of fuel types. They constructed a fuel moisture index, F, as a function of ($T - H$) (Table 1). Comparison with existing FMC models (McArthur 1967; Simard 1968; Anderson *et al.* 1978; Nelson 1984; van Wagner 1987) showed monotonic but non-linear relationships, meaning that for fuel types where those models are applicable, F can be used as a rule of thumb to estimate relative FMC. For applications requiring actual FMC values it is likely to be simpler to use the models rather than applying non-linear corrections to the F. Sharples and Matthews (2011) and Sharples and McRae (2011) also found that with a fuel-specific calibration coefficient, F could be used to predict FMC values with a similar level of accuracy to eucalypt models such as those of Sneeuwjagt and Peet (1996) and Matthews *et al.* (2010).

Weise et al. *(2005)*

Weise *et al.* (2005) investigated the FMC of 15 species at 11 sites in Hawaii, including loblolly (*Pinus taeda*), slash (*P. elliottii*) and Monterey (*P. radiata*) pine needles, eucalyptus (*Eucalyptus robustus* Sm.) leaves, eight native and exotic grasses (velvet grass, *Holcus lanatus* L.; alpine hairgrass, *Deschampsia nubigena* Hbd.; buffelgrass, *Pennisetum ciliare* (L.) Link; guinea grass, *Urochloa maxima* (Jacq.) R. Webster; Hawaiian lovegrass, *Eragrostis atropioides* Hbd.; broomsedge, *Andropogon virginicus* L.; beardgrass, *Schizachyrium condensatum* Kunth (Nees); fountaingrass, *Pennisetum setaceum* (Forsk.) Chiov.). Destructive sampling was used to measure FMC hourly for 78–101 h in late summer in 2000 and 2001. A Markov Chain model was fitted to the observations using site weather. FMC was predicted from EMC and previous FMC:

$$m_t = (1 - \beta)m_e + \beta m_{t-1} \qquad (8)$$

where β is an empirical parameter. This model had varying success with R^2 ranging from 0.1 to 0.8, but tended to under-predict for all species.

Zhang et al. *(2006)*

Zhang *et al.* (2006) measured the FMC of litter in a fir (*Cunninghamia lanceolata* (Lamb.) Hook.) plantation in China. Plots were established on the south-west-, north-west- and north-east-facing slopes of a hill with a slope of 32°. FMC in each plot was measured by destructive sampling three times per day for 2 days in 2003. Multiple linear regression was used to fit models against subsets of H, U, T and surface temperature ($T_{surface}$). Models were then validated against 2 days of measurements in 2004. The model with highest correlation used H, T and $T_{surface}$ (Table 1). Average relative error was 10%.

Process-based models

There is scope for a variety of approaches to constructing process-based models, although all models reviewed here have energy and water balance conservation equations as a common element. Models are presented below in an order reflecting their structure: bulk litter layer models in which interception and evaporation are the main processes, models based on Byram's diffusion equation and complete process-based models.

Heikinheimo et al. *(1996)*

Heikinheimo *et al.* (1996) developed a water balance model for a 6 cm-deep layer of pine litter and duff in a forest clearing. A clearing rather than a forest stand was selected on the basis that this would be the driest part of the landscape and to simplify the model specifications. Increase in water storage due to rainfall is modelled as an empirical function of observed rainfall. Evaporation is calculated 3 hourly using the Penman–Monteith equation for potential evaporation (Monteith and Unsworth 1990) modified by an empirical drying factor that decreases from 0.7 for saturated fuels to 0 for dry fuel. The empirical wetting and drying functions were determined from measurements made in a forested site and three clearings over 3 months in 1995. Predictions were found to be within the envelope of observations for the clearings. This model is used operationally as part of the Finnish Fire Weather Index (Venäläinen and Heikinhemio 2008), which has been found to be a useful predictor of fire occurrence in Finland (Tanskanen and Venäläinen 2008).

Schaap et al. *(1997)*

Schaap *et al.* (1997) modified a soil moisture model (Tiktak and Bouten 1992) to predict the FMC of the forest floor in a Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forest, with litter included as the top layer of the model. Litter heating and evaporation were modelled using a modified Penman–Monteith equation in which resistance to evaporation was included as an empirical function of FMC (Schaap and Bouten 1997). Vertical movement of liquid water (i.e. interception and drainage of rainfall and uptake of water by the litter) was predicted by the soil model's retention and conductivity sub-models. The model is thus conceptually similar to the Heikinheimo *et al.* (1996) model but includes a more complete description of soil and litter moisture dynamics. Model parameters were calibrated using measurements for 325 days in 1992 at three sites, then tested for 367 days in 1992–93. FMC observations were spatially variable but temporally correlated. The model was capable of simulating observed moisture content, although accuracy was limited by the temporal resolution of weather observations. This model does not appear to have been used operationally.

Tamai (2001)

Tamai (2001) developed a bulk water balance model for use in forest litter. FMC is increased by rainfall up to the litter's holding capacity of 200%, after which it runs off. Evaporation is modelled as an empirical function of FMC and solar radiation. The model was initially calibrated using laboratory lysimeter measurements and predictions were found to correlate with fire occurrence in two forest types in western Japan. Subsequently, Tamai and Goto (2003) calibrated the model for an oak (Q*uercus serrata* Thunb. Ex. Murray) and longstalk holly (*Ilex crenata* Thunb.) forest plot in Japan. The model was tested against measurements made on 26 days in 2000 and 2001. FMC observations below 40% were well predicted but the model under-predicted in wetter conditions. Tamai and Goto (2008) applied the model to examine spatial variation in FMC in a 40-ha area of forest in western Japan. Large variations in FMC due to spatial variation in topography and forest structure were simulated, but predictions were not tested against observations.

Catchpole et al. *(2001)*

Catchpole *et al.* (2001) developed a piecewise approximation method of integrating Byram's equation (Eqn 1):

$$m_t = \lambda^2 m_{t-1} + \lambda(1-\lambda)m_{e,t-1} + (1-\lambda)m_{e,t} \tag{9}$$

where $\lambda = \exp(-\delta t/2\tau)$. Using the Nelson (1984) formula for EMC (Eqn 2) and constant response time the model was fitted to FMC observations collected in eucalypt (*Eucalyptus rossii* and *E. macrorhyncha*) (Viney and Catchpole 1991), mallee (*Eucalyptus* spp.) (McCaw 1998) and buttongrass (Marsden-Smedley and Catchpole 2001) fuels. For all fuels this approach yielded good model fit and parameters that were similar to those obtained for other fuels types in laboratory studies. The methods developed by Catchpole *et al.* (2001) have also been applied to gorse (Anderson and Anderson 2009) and heath species (Pippen 2008).

Fiorucci et al. *(2008)*

As part of the development of a wildfire risk assessment model, Fiorucci *et al.* (2008) produced an FMC model. This model has two additions to the Byram equation (Eqn 1). First, in the absence of rain, EMC is a function of temperature, wind speed and humidity, and after rainfall EMC is set to a constant value. Second, the rate of drying depends on temperature, wind speed, humidity and rainfall. Fiorucci *et al.* (2008) did not attempt to parameterise the model from observations but instead parameters were estimated during calibration of the entire scheme against fire occurrence data from Italy. Although the fire risk system performed adequately, no information about the performance of the FMC model was given.

Qu et al. *(2010*a*)*

Qu *et al.* (2010*a*, 2010*b*) developed a model for the moisture content of a hollow basswood stick. Response time was constant and EMC was modelled as a function of relative humidity, air temperature and wind speed. The model was calibrated using 1149 hourly measurements from an automatic weather station and stick mass measured on a logging balance. The model was testing using 200 observations and found to have average relative error of 5%.

*Wotton (2009*a*)*

Wotton (2009*a*) adapted the hourly FFMC (van Wagner 1977) for cured grass by including appropriate EMC (van Wagner 1972), response time (Anderson 1990*b*) and rainfall absorption calibrations. A fuel temperature equation to account for solar heating was also added (van Wagner 1969). The model was tested against 8 days of samples collected during daylight hours, including two rain events. Diurnal cycles and drying after rainfall were simulated correctly and errors were lower than for predictions made using the original FFMC.

Nelson (2000)

Nelson (2000) developed a model for the 10-h hazard rod FMC used as part of the NFDRS (Burgan 1988). As 10-h hazard rods are coarse fuels, movement of water within this fuel is included in the model, in contrast to other models reviewed here. Radial movement of heat and water within the fuel is modelled as a diffusion process with diffusivity a function of FMC. The surface temperature of the rod is predicted using an energy balance equation in which the surface is assumed to be always in equilibrium with surrounding conditions. The surface water balance includes interception of rainfall, evaporation and dew formation. Interception of precipitation is predicted as an empirical function of rainfall amount, whereas evaporation is a function of vapour pressure deficit. Model equations are solved at a 1-h timestep using observations or forecasts of air temperature, relative humidity, solar radiation and rainfall.

Testing using 32 days of observations in June, August and September 1993 showed the model could predict hazard rod moisture content in both wet and dry conditions. The model was also compared with observations of 1-, 10-, 100- and 1000-h hazard rods made in the USA in 1996 (Carlson *et al.* 2007). Predictions from the Nelson (2000) model were found to be better than NFDRS models for all size classes. Weise *et al.* (2005) used Nelson's and other models to predict the moisture content of 15 species at 11 sites in Hawaii. Model performance was mixed but in many cases the Nelson model was the best performing. This model is currently used operationally to predict hazard rod moisture content for the NFDRS.

Wittich (2005)

Wittich (2005) developed a bulk litter model that differs from those reviewed above by including vapour sorption processes at low moisture contents. This makes the model more versatile because it can be used to simulate diurnal cycles in FMC driven by relative humidity as well as wetting and drying associated with rainfall. A single water transport equation is used for the litter layer, but separate budget terms are calculated for water stored in the fuel and on the fuel surfaces. The moisture budget includes interception of precipitation and dew, drainage to the soil, absorption of surface water, evaporation and vapour exchange by the litter. Movement of water from the soil to litter by capillary action is ignored (c.f. Schaap and Bouten (1997) above). The litter energy budget includes short- and long-wave radiation exchange, heat transfer to the atmosphere and latent heating due to water vapour fluxes. Soil heat flux is ignored. Use of the model requires specification of parameters to describe the litter and measured weather conditions: air temperature, wind speed, humidity, rainfall rate, solar radiation and thermal radiation.

Two tests of the model were performed. In the first experiment, a tray of spruce (*Picea abies*) needle litter was exposed inside a Stevenson screen for 30 days in July 2000. In the second experiment, a tray of pine (*Pinus sylvestris*) needle litter on a lysimeter was exposed to the weather in a grassed area for 30 days in July 2000. In both experiments the model was able to simulate FMC during both rainy and dry conditions. Although error statistics were not calculated, simulated FMC was within a few percent during non-rainy conditions and the lengths of drying cycles after rain were correct to within a day.

Matthews (2006)

The Koba model (Matthews 2006) is a multi-layer, process-based model that represents fluxes of energy and water in a litter bed composed of 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 materials is calculated at five equally spaced nodes within the litter layer using equations for the energy and water balance of the three materials. A model for suspended fuel has also been derived (Matthews and McCaw 2006).

This model is the most detailed of the process-based models, using multiple layers within the litter bed and including most of the processes described above. It is also the most difficult to implement, requiring 26 parameters to describe the litter layer, and the boundary conditions required are: air temperature, wind speed, specific humidity, rainfall rate, solar radiation, thermal radiation, soil temperature and soil moisture. The model has performed adequately in testing studies (Matthews *et al.* 2007; Cruz *et al.* 2010). In non-rainy conditions FMC was predicted with mean absolute error of 3% and across all observations flammability was predicted correctly for 80–90% of measurements (Matthews *et al.* 2007). Because implementation of the model is challenging, simpler versions have been developed for non-rainy conditions (Matthews *et al.* 2010). The model has been applied in climate change studies for which the required inputs are readily available from global climate models (Matthews *et al.* 2011, 2012). Elements of the Koba model were used by Haverd and Cuntz (2010) to include a litter layer in a forest surface layer model. Koba has also been used to reconstruct FMC conditions during the 2009 Black Saturday bushfires in Victoria, Australia (Sullivan and Matthews 2013).

Testing and application of existing models to new measurements

Extensive work has been done comparing the predictions of FMC models with field observations (Table 2), with studies carried out for three purposes: calibration of models in new fuel types, validation of models in the fuels where they are normally used and application of a range of models in a new fuel to determine which can be used with the new fuel.

Calibration studies examined whether a model structure is suitable in the new fuel type and provide parameters for future application. These studies have been most commonly used for process-based models and for the Canadian fire weather index (FWI) system (van Wagner 1987), which allows specification of empirical relationships between model indices and FMC. Models have generally been found to be suitable and this work has expanded the number of fuel types for which predictions can be made. Compared to calibration and application studies, relatively few validation studies have been published, and these have also focussed on process-based models and the FWI components.

In application studies, predictions from a range of models have been tested with the result either that one was recommended for the new fuel or a new empirical model was derived. Since most models use similar equations with differing parameters (see e.g. Table 1 and Ruiz Gonzalez and Vega Hidalgo 2007) it is likely that if enough models are tested on a dataset one will be a reasonable fit. It might be better to calibrate a model that allows this or to simply fit new parameters to Eqn 6, rather than picking an existing model that coincides with the new data. On the other hand, if the selected model is already in use then its application to a new fuel may be operationally expedient.

Discussion

Considerable progress has been made in understanding fuel moisture processes since Viney's review. Viney (1991) identified four topics for future research: better prediction of fuel level air temperature and humidity, the effect of litter structure on FMC, interception of precipitation and partitioning of precipitation into absorbed and free components. The experimental and modelling work reviewed here has provided understanding and models of these processes. Integration of knowledge from other fields, such as forest hydrology, has also improved understanding of FMC processes.

There have been useful developments in characterising FMC in the landscape and more is now known about the effects of fuel structure, micrometeorology and topography. There also remain some significant unanswered questions. For example, the effects of soil moisture on litter moisture have been clearly demonstrated for pine fuels, but it remains to be seen whether these effects are also significant for hardwood litters. It is commonly assumed that geometrical methods can be used to predict radiation on sloping ground, and temperature. However, experimental work has been equivocal, with radiation effects conflated with or overwhelmed by vegetation structure or micrometeorology.

Whereas before 1991 all models in use were empirical or semi-empirical there are now process-based models for woody, litter and suspended fuels. These models have been shown to

Table 2. Studies comparing model predictions with measurements

Rows are the models tested, columns are individual studies. Models are sorted in alphabetical order of the citation describing the model. Table entries indicate studies in which models were: C, calibrated for a new fuel type; V, validated in an existing fuel type; or A, applied to a new fuel type

Reference	Model name	Anderson and Anderson (2009)	Anderson (2009)	Beck and Armitage (2004)	Carlson *et al.* (2007)	Cruz *et al.* (2010)	Estes *et al.* (2012)	de Groot *et al.* (2005)	de Groot *et al.* (2007)	Krivtsov *et al.* (2010)	Lopes *et al.* (2010)	Marsden-Smedley and Catchpole (2001)	Matthews *et al.* (2007)	Matthews *et al.* (2010)	Otway *et al.* (2007)	Pippen (2008)	Plucinski (2003)	Pook and Gill (1993)	Ruiz Gonzalez *et al.* (2002)	Ruiz Gonzalez *et al.* (2009*b*)	Sharples and Matthews (2011)	Sharples and McRae (2011)	Slijepcevic and Anderson (2006)	Tanskanen *et al.* (2006)	Viegas *et al.* (1992)	Weise *et al.* (2005)	Whitehead *et al.* (2008)	Wilmore (2001)	Wotton *et al.* (2005)	Wotton and Beverly (2007)	Wotton (2009*b*)
Anderson *et al.* (1978)												A								A											
Catchpole *et al.* (2001)		C														C	C			A			A								
Deeming (1977)	NFDRS																		A							A					
Fosberg *et al.* (1981)	NFDRS 1000 h						V																								
Fosberg and Deeming (1971)	NFDRS 10 h						V																								
Gill *et al.* (1987)												A							A												
Heikinheimo *et al.* (1996)																								V							
King and Linton (1963*b*)																				A											
Marsden-Smedley and Catchpole (2001)																A	A			A			A								
Matthews (2006)	Koba					C							C	V		C					V										
McArthur (1962)	CBEF											A				A	A	A	A	A			A								
McArthur (1966)	GFDM											A					A	A	A	A			A								
McArthur (1967)	FFDM											A				A	A	A	A	A			A								
Nelson (1984)												C					C			A											
Nelson (2000)	10-h hazard rod				V																					A		V			
Pech (1989)	reindeer lichen											A					A														
Pook (1993)												A					A	A					A								
Rothermel (1983)	FBO																		A	A											
Rothermel *et al.* (1986)	BEHAVE																		A						A						
Ruiz González *et al.* (2009*a*)																				A											
Sharples *et al.* (2009)	FMI																				C	C									
Simard (1968)												A					A			A											
Sneeuwjagt and Peet (1996)	Red Book															A				A	V		A								
van Wagner (1972)												A																			
van Wagner (1987)	FFMC	C	V	C				C	C	A	A						A		A	A			A				V			C	C
van Wagner (1987)	DMC									A	A				C													V	C	C	C
van Wagner (1987)	DC								C	A	A				C																
Vega and Casal (1988)																			A	A											
Weise *et al.* (2005)																										C					

work well and will be a foundation for modelling landscape FMC but there is scope for improvement of process-based models. In particular, soil moisture has been shown to have an effect on FMC through capillary uptake of water in pine fuels. Neither of the two full process-based models (Wittich 2005; Matthews 2006) take this into account, and other water balance models (Heikinheimo *et al.* 1996; Schaap *et al.* 1997; Tamai 2001) are not suitable for predicting diurnal cycles.

On the other hand, empirical models have continued to prove useful, particularly when fuels are not affected by rain, and where limited weather data or computing power are available. However, some of the empirical models described here have been constructed using only a few days' data covering a narrow range of weather conditions. Where longer experimental measurement campaigns are not possible, field validation is needed to ensure these models are valid in operational use.

All the models reviewed here are point based, assuming that site specific meteorological observations or predictions can be provided. Several frameworks have been developed with embedded FMC models for making landscape-scale predictions (Finney 1998; Tolhurst *et al.* 2008; Holden and Jolly 2011; Sullivan and Matthews 2013). These make site-specific

FMC predictions by correcting weather inputs for altitude, slope and aspect and, in some cases, effects of vegetation type on radiation. However, because no suitable spatial FMC datasets have been published it is currently unknown whether these systems provide accurate predictions. Experimental measurements of spatial variation in FMC should be conducted in future and can be expected to lead to interesting results and improvements to models.

Little work has been done to examine how FMC forecasts should be made. Historically, fire weather predictions including the FMC models used in the indices (McArthur 1967; van Wagner 1987; Burgan 1988) have been made using fire weather forecasts of temperature, relative humidity, wind speed and daily rainfall. However, gridded forecast products are now available for many fire-prone parts of the world (Glahn and Ruth 2003; Persson and Grazzini 2005; Anon. 2012). These forecasts include quantities such as cloud cover, which are not used by existing operational models but are known to affect FMC. Whether use of gridded forecasts with process-based models can improve FMC predictions should be investigated. It may also be useful to attempt direct coupling of FMC models to weather forecast models to allow computation at timescales applicable to FMC processes (e.g. 1 h) rather than at the 3- or 6-h intervals at which forecasts are produced. This would also allow FMC models to directly use inputs, such as solar radiation, which are not included in weather forecasts.

The models examined here are deterministic but many model inputs are uncertain either because weather forecast variables are uncertain or because there are variations in forest or fuel structure that cannot be practically resolved, for example random variations in fuel depth or forest canopy gaps. This means that even if an FMC model is a perfect representation of all relevant physical processes there is still an irreducible uncertainty in the output (Albini 1976). Ensemble methods to map uncertainty from inputs to predictions have been used for fire behaviour models (Anderson *et al.* 2007; Cruz 2010) and this approach could also be applied to FMC.

Chandler *et al.* (1983) noted that:

> the history of attempts to accurately predict fuel moisture contents of forest fuels have been an endless series of beautiful theories demolished by ugly facts.

The work reviewed here confirms that the facts continue to be, if not ugly, at least very complex due to the interactions of weather, topography, vegetation and FMC. However, our theories have advanced to deal with this complexity. The use of an energy and water balance approach has resulted in models that work well in a given location, even if these models require numerical solution of differential equations and can perhaps not be considered beautiful. On the other hand, the simple theory of exponential decay towards EMC, which is at the heart of all fuel moisture models, has continued to prove useful provided care is taken in its application.

Considering the last 20 years of dead FMC research there are several areas where there is potential for interesting future research. First, some aspects of FMC physics remain unresolved. In particular, one task still remaining from Viney's list is the validation of fuel temperature predictions. Although several models can now predict this quantity (Byram and Jemison 1943; Rothermel *et al.* 1986; Wittich 2005; Matthews 2006) adequate validation has not been performed. Also, the role of soil moisture in determining FMC remains uncertain and it still remains to develop a process-based model that includes both soil moisture and vapour exchange processes. The second major area for research is model application, most importantly being able to represent the complexity of vegetation structure and topography and forecast FMC across the landscape. Other useful developments would include making better use of gridded weather forecasts and incorporation of uncertainty into FMC predictions.

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