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Estimating fuel response time and predicting fuel moisture content from field data

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Abstract. We develop a method for estimating equilibrium moisture content (EMC) and fuel moisture response time, using data collected for *Eucalyptus* twig litter. The method is based on the governing differential equation for the diffusion of water vapour from the fuel, and on a semi-physical formulation for EMC (Nelson 1984), based on the change in Gibbs free energy, which estimates the EMC as a function of fuel temperature and humidity. We then test the model on data collected in Western Australian mallee shrubland and in Tasmanian buttongrass moorland.

This method is more generally applicable than those described by Viney and Catchpole (1991) and Viney (1992). The estimates of EMC and response time are in broad agreement with laboratory-based estimates for similar fuels (Anderson 1990*a*; Nelson 1984).

The model can be used to predict fuel moisture content by a book-keeping method. The predictions agree well with the observations for all three of our data sets.

Keywords: buttongrass moorland, *Eucalyptus* litter, equilibrium moisture content, fuel moisture content, mallee, response time, time-lag.

Introduction

Estimates of the moisture contents of components of a vegetation complex are needed for prediction of fire behaviour in hazard-reduction burning and in wildfire situations. Decreased fuel moisture content increases the fire intensity, spread rate and probability of ignition. In some situations, such as hazard-reduction burning, near real-time fire behaviour predictions are needed. This rules out gravimetric analysis, which takes a minimum of 24 hours before results are obtained. Moisture meters, such as the Speedy and the Marconi (see e.g. Dexter and Williams 1976) are prone to error. The Wiltronics meter (Chatto and Tolhurst 1997), and the Neosystems meter (Neosystems Inc., Perth, W.A.) are expected to provide more precise moisture content measurements in many situations. However, measuring devices cannot predict moisture content at a distant site, or in the future. These needs occur when predicting fire danger, predicting the probable behaviour of a wildfire, or making decisions about hazard-reduction burning from an operations centre. We review some methods of estimating moisture content, and introduce a new method which has several advantages over existing methods.

The moisture content of a particle of fuel introduced into an environment of constant temperature and humidity increases or decreases until it eventually reaches a steady moisture content called the *equilibrium moisture content* (EMC) which is a function of the fuel temperature and humidity, fuel particle characteristics, and whether the particle has been adsorbing or desorbing moisture. The EMC for adsorption is generally about 2% lower than that for desorption. In field situations, where the temperature and humidity change with time, the moisture content of the particle lags behind the EMC. Knowledge of how fast the particle responds to changes in temperature and humidity of the environment is

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needed in order to formulate a predictive model for moisture content.

From diffusion theory the differential equation below provides an approximation to both the adsorption and desorption processes of small diameter fuel (Byram 1963)

$$\frac{\mathrm{d}m}{\mathrm{d}t} = -\frac{m - q}{\tau}, \tag{1}$$

where m is the fuel particle moisture content at time t, q is the equilibrium moisture content, and τ is a constant known as the *response time* of the fuel. The solution of the differential equation for constant q shows that τ is the time to accomplish about 63% of the change from the initial moisture content of the fuel to the EMC. Response time is closely related to the size of the fuel particle, but other characteristics, such as density, shape, surface coating and weathering, also affect the response time (Anderson 1990*a*).

Several researchers have developed equations for the equilibrium moisture content of various fuels. Simard (1968) developed an equation for the average EMC of wood under desorbing conditions. Van Wagner (1972) gave equations for the EMC of forest litter under adsorption and desorption conditions. Anderson *et al.* (1978) modified Van Wagner's equations to describe the EMC of *Pinus ponderosa* litter. These equations are given by Viney (1991), who discusses their merits and applicability.

The Canadian Forest Fire Weather Index (Van Wagner 1987) uses equations based on the solution of (1), Van Wagner's formulas for EMC, and a formula for response time in terms of temperature, humidity and windspeed. The model predicts the moisture content in terms of the current EMC and the fuel moisture content of the previous time period, and is used as a book-keeping (iterative) method.

Viney's methods

Two methods were suggested by Viney and Catchpole (1991) and Viney (1992) for estimating the response time of fuel from data collected in the field. The first involves fitting sine wave functions to plots of moisture content and EMC versus time, and estimating the lag between the two functions. From this the response time can be calculated. The second method involves finding the time lag that gives the maximum correlation between the EMC and the lagged moisture content, and then calculating the response time as in the first method. We demonstrate these two methods on data for moisture contents of *Eucalyptus* twig litter.

The data consist of a set of hourly measurements of moisture content of *Eucalyptus* twig litter collected for 4 days from a stand of *E. rossii* and *E. macrorhyncha* in a dry sclerophyll forest on Black Mountain in the Australian Capital Territory. The data and sampling methods have been previously described in Viney and Hatton (1989). Fuel temperature was estimated from the measured screen-level air temperature, 2 m windspeed, and estimated solar radiation, using the formula of Byram and Jemison (1943). Note that this formula is based on fuel-level windspeed. Since there was a canopy in Viney and Hatton's experiment, we have assumed a constant wind profile (see for example Albini and Baughman 1979), and so no correction has been applied to the measured 2 m wind. Fuel-level humidity was then estimated from fuel temperature and screen-level air humidity, assuming no change in dew point from screen level to ground level, as in Byram and Jemison (1943). Moisture contents of leaves, twigs (with bark) and trunk bark (in the litter) were measured, but we consider here only the twigs, as the leaves and trunk bark were affected by overnight condensation. The twigs were less than 6 mm in diameter, and may be considered as fine fuel. We consider only the first 3 of the 4 days' data in Viney and Hatton (1989), for reasons discussed below.

We assume the EMC from Simard (1968), in the form given by Viney (1991). A sinusoidal function of the form

$$q(t) = \bar{q} + A \sin[\omega(t - t_0)] \tag{2}$$

can be fitted by regression methods (see e.g. Myers 1989). Here A and t_0 are constants which can be estimated from the regression, $\bar{q}$ is the average EMC, and $\omega = \pi/12$ is the angular frequency, where t is measured in hours. If the EMC follows this sinusoidal curve, the solution of the differential equation (1) has the form

$$m(t) = \bar{m} + B \sin[\omega(t - t_0 - t_{\mathrm{lag}})], \tag{3}$$

where B is a constant, $\bar{m}$ is the average moisture content, and t_{lag} is the time lag by which the moisture content curve lags behind the EMC curve. The response time is then given by

$$\tau = \frac{1}{\omega} \tan(\omega t_{\mathrm{lag}}), \tag{4}$$

(Viney and Catchpole 1991). A sinusoidal curve of the form (3) can be fitted to the moisture content data to estimate t_{lag}, and hence τ can be estimated from (4).

Sinusoidal curves are shown fitted to the moisture content and EMC data in Fig. 1. From these the estimated t_{lag} is 0.92 h (with standard error, s.e., 0.23 h), and from (4) τ is estimated to be 0.93 h (s.e. 0.24 h) (Viney and Catchpole show that t_{lag} and τ are very nearly the same for $\tau < 1$ h). The sine wave functions fit reasonably well, but tend to underestimate the moisture content at the peaks.

To use Viney's second method we first fit interpolation splines (see e.g. Lancaster and Salkauskas 1986) to the EMC and the moisture content data, as shown in Fig. 2. We choose the interpolation splines to have points q_k and m_k every 0.01 h. We then find the maximum correlation

$$\max_{\ell}\{\mathrm{corr}(m_{k-\ell}, q_k)\}. \tag{5}$$

The time lag corresponding to this maximum is t_{lag}. This method gives a time lag of 0.99 h, and a response time of 1.01 h, with a maximum correlation of 0.94.

The sine wave method has the advantage over the correlation method of giving standard errors for the estimates, and of giving a relationship between response time and lag time. It has the disadvantage of relying on sinusoidal behaviour of the equilibrium and fuel moisture contents. From Fig. 1 this appears to be a reasonable approximation. However in Viney and Hatton (1989), the fourth night of observation was overcast, warmer, and less humid than the first three nights. The EMC curve differed markedly, and the assumption of a constant amplitude sine curve over the entire data set becomes untenable.

The correlation method has the advantage of not requiring a sinusoidal assumption, although in this case the relation (4) holds only approximately. This method also fails to give standard errors.

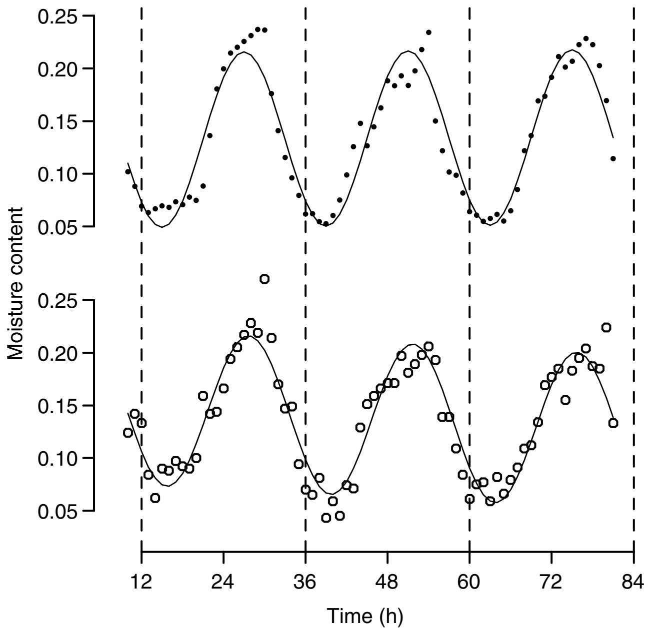

Fig. 1. Moisture contents of *Eucalyptus* twigs (open circles) and the fitted sine curve. Also shown are Simard's EMC values (filled circles) and the fitted sine curve. The dotted vertical lines are at midday each day.

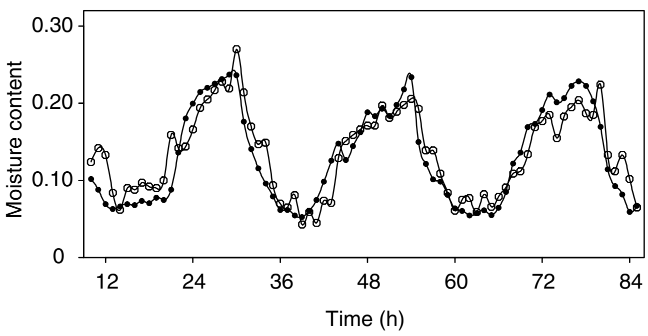

Fig. 2. Interpolation splines for the *Eucalyptus* twigs fitted to moisture contents (open circles) and Simard's EMC (filled circles).

Note also that both the above methods rely on a known EMC, which requires laboratory drying experiments that may not have applicability in the field. So far we have assumed Simard's equations for the EMC, as in Viney (1992). These equations were developed for North American timber curing. As Simard (1968) notes, the equations are species dependent, and so may be inappropriate for *Eucalyptus* twigs.

We now introduce a new method, based on the governing differential equation (1), which overcomes these problems. In order that our results be comparable with those using Viney's methods, we will continue to use just the first 3 days of the Viney and Hatton (1989) data.

Differential equation (DE) method

Equation (1) is a first-order differential equation which can be solved in any time interval (t_i, t_{i-1}) to give

$$m(t_i) = \exp\left(-\frac{\delta t}{\tau}\right)\left\{m_{i-1} + \frac{1}{\tau}\int_{t_{i-1}}^{t_i} \exp\left(\frac{t - t_{i-1}}{\tau}\right) q(t)\,\mathrm{d}t\right\}, \tag{6}$$

where $\delta t = t_i - t_{i-1}$ is the sampling interval for the moisture content. Hence, if we know $m_{i-1} = m(t_{i-1})$ and we know q as a function of t in the interval (t_{i-1}, t_i), we can calculate a predicted moisture content $\hat{m}_i$ at t_i.

To find the EMC q as a function of time we fit a spline through the points where the EMC is known (as in Fig. 2). For the present we use Simard's formula for the EMC. Here we have assumed that the temperature and humidity are measured accurately, and thus the EMC is known accurately, and so we have used an interpolation spline. The points of the spline are set to be at intervals of $\delta t/10$, so we have an estimate of the EMC at 10 points in each interval (t_{i-1}, t_i). These can be used to evaluate the integral in (6) numerically.

A somewhat less accurate approximation to the EMC curve is to replace the spline by a piecewise constant curve, as shown in Fig. 3. That is,

$$q(t) = q_i, \qquad t_i - \delta t/2 < t < t_i + \delta t/2.$$

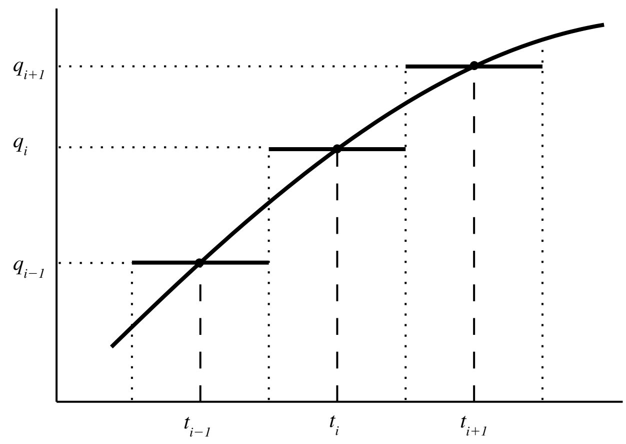

Fig. 3. Spline interpolation through the EMCs, and the piecewise-constant approximation.

This centres the piecewise approximations about the observed values, which is necessary to avoid the introduction of a spurious time lag. Note that Van Wagner (1987) uses a piecewise approximation without centering.

Substituting the piecewise approximation into (6) gives

$$m(t_i) = \lambda^2 m_{i-1} + \lambda(1-\lambda)q_{i-1} + (1-\lambda)q_i, \qquad (7)$$

where $\lambda = \exp(-\delta t/(2\tau))$.

To estimate τ we chose that value of τ which minimises the sums of squares of errors

$$SSE = \sum_{i=1}^{n}(m_i - \hat{m}_i)^2, \qquad (8)$$

where $\hat{m}_i$ is given by the right-hand side of (6) or (7). This can be minimised using non-linear regression (Myers 1989). This gives both an estimate for τ and an asymptotic (large n) standard error. Applying this to the *Eucalyptus* twig data and using the spline method, the response time τ is estimated to be 1.40 h with standard error 0.20 h. Using the piecewise approximation, equation (7), the corresponding results are 1.38 h and 0.18 h respectively.

Once τ is known the method can be set up to calculate a predicted moisture content m_{pred}, via a book-keeping method. First $m_{\mathrm{pred},1}$ is set equal to the EMC at t_1. Then, for $i \geq 2$, $m_{\mathrm{pred},i}$ is calculated in terms of $m_{\mathrm{pred},i-1}$ from equations (6) or (7), by substituting $m_{\mathrm{pred},i-1}$ for m_{i-1} and $m_{\mathrm{pred},i}$ for $m(t_i)$. All that is required is an estimate of the EMC at each time point.

Use of Nelson's formula for EMC

The advantage of the DE method is that it gives a direct estimate of the response time τ, and an asymptotic standard error, without the need to assume a sinusoidal form for the EMC. However when using this method above we needed to assume a possibly inappropriate formula for the EMC. To deal with this problem we now consider a general form for the EMC, based on physical considerations, postulated by Nelson (1984). Nelson modelled the EMC as a linear function of the change in the logarithm of the Gibbs free energy, ΔG, of the fuel particle, so that

$$q = a + b\log\Delta G = a + b\log\left\{-\frac{RT}{M}\log H\right\}, \qquad (9)$$

where a and b are constants, T is temperature (Kelvin), H is the (fractional) relative humidity, R is the universal gas constant, and M is the molecular weight of water. Nelson (1984) found a and b to depend on fuel type and also on whether the fuel was adsorbing or desorbing. Anderson (1990*b*) found that a and b also depend on the temperature T, although the dependence is fairly weak. We therefore neglect this dependence, and also choose a single equation of the form (9) to apply over the whole data set, both adsorbing and desorbing conditions. This is pursued further in the Discussion.

We can now replace q in equation (6) or (7) by equation (9), and then minimise SSE simultaneously for a, b and τ, to give estimates of both the EMC and the response time. For the *Eucalyptus* twig data, using spline interpolation, this produces estimates of a, b and τ of 0.26, −0.051, and 1.03 h respectively, with asymptotic standard errors as shown in Table 2.

For this model the mean absolute error (MAE), defined as $\sum_i |m_i - \hat{m}_i|/n$, is 0.013, and the root mean square error (RMSE), defined as $\sqrt{\sum_i (m_i - \hat{m}_i)^2/n}$, is 0.018. The MAE is a more robust estimate of the average error in that it is less sensitive to outliers. These average values are for the errors arising from (6), which gives $\hat{m}_i$ in terms of m_{i-1}. In other words, we are predicting just one hour ahead of a fuel moisture content measurement.

A more realistic assessment of the errors can be obtained by using the above parameter estimates and predicting the whole data set using the book-keeping method described above. The observed and predicted moisture contents using this method are shown in Fig. 4.

We start the book-keeping predictions from the EMC: $m_{\mathrm{pred},1} = q_1$. This choice is for want of a better estimate. In practice the choice is unimportant as the system soon settles down into predictions that do not depend on the initial value chosen. However it takes some time to 'forget' the initial condition and so, in assessing the goodness of fit of the book-keeping predictions, we allow a time of $3\tau = 3.1$ h for this—that is, we omit the first three hourly observations. When this is done, the average errors become MAE $= 0.013$ and RMSE $= 0.017$. These values are as good as for the predictions obtained using the actual fuel moisture contents to predict an hour ahead.

The results for response time τ for the four different methods are summarised in Table 1. As can be seen, the DE method with Nelson's EMC agrees well with Viney's methods and gives the most precise estimate. The DE method using Simard's EMC gives an appreciably larger value than the other methods. A reasonably good model for EMC appears to be

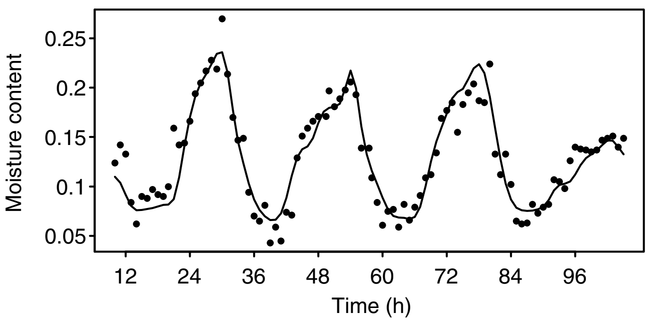

Fig. 4. Observed (dots) and predicted (line) moisture contents for *Eucalyptus* twig data using the DE method with Nelson's model for EMC.

necessary to get a good result for τ from the DE method. Note that the data here, with 3 days of fairly closely replicated weather, were chosen so that Viney's methods are applicable. Under more variable conditions we expect the DE method with Nelson's EMC to be the most robust, as it is the most physically based.

Application to buttongrass and mallee

Mallee

We now use the DE method to estimate the response time and EMC for moisture content of litter and dead aerial fuel in *Eucalyptus* mallee vegetation in Western Australia. The vegetation consists of a stratum of multi-stemmed eucalypts about 4m tall and with a cover of 40%, above a discontinuous stratum of woody shrubs up to about 0.7 m tall. Five 0.2 m × 0.3 m black plastic seedling trays, with 1 cm open-mesh bottoms, each containing 20–30 g of *Eucalyptus* litter fuel, were weighed every hour for $2\frac{1}{2}$ days. Afterwards the fuel moisture contents were calculated by oven drying at 105°C for 18 h. Litter moisture contents were also estimated destructively from the average of three samples of 20–30 g each, taken near the litter baskets, and oven-dried at 105°C for 18 h. Five bundles of elevated fuel were weighed every hour. These bundles were loosely packed, and were intended to be representative of the elevated dead fuel of the shrubs (principally of *Dryandra drummondii*). Fuel temperature was measured using thermocouples, and fuel-level humidity was estimated from Byram and Jemison (1943). The data and further experimental details are given in McCaw (1998).

Table 1. Estimates of fuel response time, τ, and its standard error, for the *Eucalyptus* twigs, using four different methods

Method	τ	s.e. (τ)
Sine curve	0.93	0.24
Correlation	1.01	—
DE + Simard EMC	1.40	0.20
DE + Nelson EMC	1.03	0.16

The data are shown in Fig. 5. Note that these data clearly violate the assumption of Viney and Catchpole (1991) of a constant-amplitude sine wave.

Using the DE method with Nelson's EMC, and spline interpolation, we estimate the response time of the litter to be 2.02 h (s.e. 0.29 h) from litter baskets and 1.63 h (s.e. 0.32 h) from the destructive samples. These estimates are not statistically significantly different, and the values seem reasonable, as the litter was only 1–2 cm deep and lay over sandy soil. The response time of the aerial fuel is estimated to be 3.84 h (s.e. 0.40 h). This large value may be a species-linked characteristic, perhaps due to residual waxes or oils in the leaves. These estimates are shown in Table 2.

Figure 5 shows the predicted as well as the observed moisture contents. As with the *Eucalyptus* twigs, these are

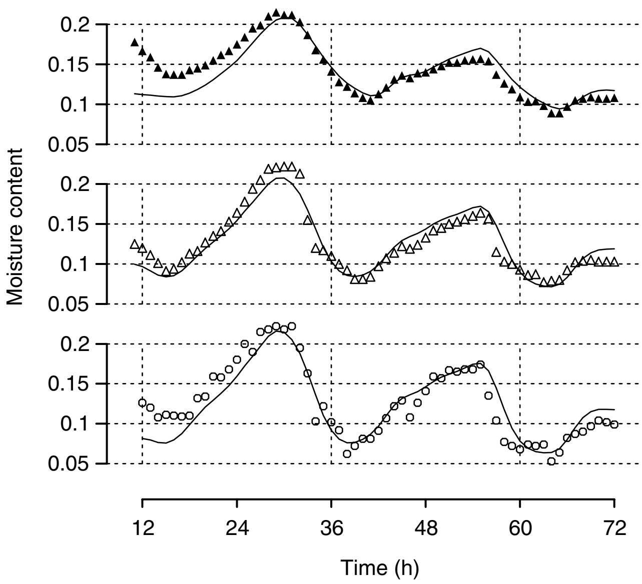

Fig. 5. Moisture contents for mallee vegetation: aerial fuel (filled triangles), litter baskets (open triangles), and litter samples (circles), together with the predicted book-keeping values (lines) from the DE method with Nelson's model for EMC. The dotted vertical lines are at midday each day.

Table 2. Estimates and standard errors for the differential equation-based moisture content model fitted to data sets

The goodness-of-fit statistics MAE and RMSE are for book-keeping predictions for the *Eucalyptus* twigs and Mallee data, and 2 h ahead of a fuel moisture measurement for the buttongrass. The KL grass values are from fitting Nelson's model to laboratory data for tussock grass given in King and Linton (1963)

Source	a	s.e.(a)	b	s.e.(b)	τ	s.e.(τ)	MAE	RMSE
Eucalyptus twigs	0.26	0.01	−0.051	0.003	1.03	0.16	0.013	0.017
Mallee litter samples	0.33	0.02	−0.069	0.005	1.63	0.32	0.013	0.016
Mallee litter baskets	0.32	0.01	−0.063	0.004	2.02	0.29	0.011	0.012
Mallee aerial fuel	0.37	0.02	−0.076	0.005	3.84	0.40	0.008	0.009
Buttongrass moorland	0.28	0.02	−0.055	0.007	1.92	0.32	0.019	0.025
KL grass adsorbing	0.29	0.01	−0.053	0.004				
KL grass desorbing	0.28	0.02	−0.051	0.004				

book-keeping predictions, starting from the initial EMC. Note that the time taken for the system to forget the initial condition is more noticeable here than for the *Eucalyptus* twigs, particularly in the case of the aerial fuel, which has the longest response time.

Mean absolute and root-mean-squared errors are also given in Table 2. As with the *Eucalyptus* twigs, these average errors omit the first 3τ predicted values, to allow time for the system to settle down. The method gives good predictions, particularly in the case of the continuously weighed samples. The higher MAE and RMSE of the destructively sampled litter results from the random error inherent in the sampling method. This inherent error can be seen in Fig. 5, where the litter basket and aerial fuel data are noticeably less variable than the litter sample data. They are less variable because the same fuel particles were sampled on each occasion.

Note that a and b, which determine the EMC estimate through equation (9), are virtually identical for basket and destructive samples. We would expect this, since the fuel types are identical and are in similar locations. This gives us some confidence in the appropriateness of the model.

Buttongrass

The fuel structure of the Tasmanian buttongrass moorlands is described in Marsden-Smedley and Catchpole (1995), and a model for fuel moisture content, using humidity and dew-point temperature measured at the time of sampling, with no time lag, is given in Marsden-Smedley and Catchpole (2001). Moisture content, temperature and humidity were measured at 2-h intervals during the daytime in 4 runs of 2–3 days following rain events in spring and summer. The data and sampling methods are as described in Marsden-Smedley and Catchpole (2001). Fuel moisture contents are shown in Fig. 6. The data are highly fragmented, and Viney's methods are clearly inappropriate here.

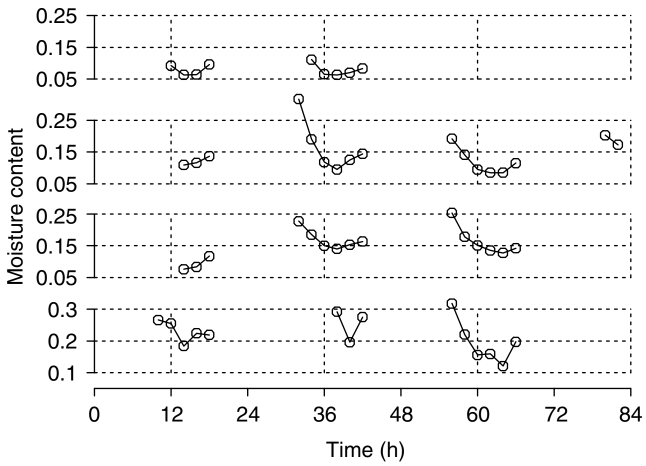

Fig. 6. Moisture content data for, from bottom to top, run 1 (spring) and runs 2–4 (summer) for the Tasmanian buttongrass moorland. The dotted vertical lines are at midday each day.

Only moisture contents below 35%, the fibre saturation point, are included in the analysis. For moisture contents below this, the fuel can be considered as unaffected by rain or dew. The dead fuel in the moorland occurs in bundles of about 10–20 fine thin spears about 20–30 cm from the ground. As with the *Eucalyptus* twigs, fuel temperature and fuel-level relative humidity were estimated from screen-level air temperature, relative humidity and solar radiation, using Byram and Jemison (1943). The measured 2 m wind was corrected down to the fuel height of 0.4 m, assuming a logarithmic profile (see for example Monteith and Unsworth 1990), which corresponds to a wind-reduction factor of 0.59.

Because of the fragmented nature of the data, the spline method is impracticable, and we use the method based on step changes in EMC, equation (7). The estimates and standard errors are shown in Table 2, and the observed versus predicted values are shown in Fig. 7. We have used only the predictions one time step (2 h) ahead of a fuel moisture measurement, again because of the fragmented nature of the data. The model fits reasonably well (MAE $= 0.019$, RMSE $= 0.025$), and better than the model of Marsden-Smedley and Catchpole (2001), which doesn't include lag, for which MAE $= 0.024$ and RMSE $= 0.036$. The estimated response time of 1.92 h is reasonable considering the propensity for the dead fuel to occur in bunches. Note that the mean absolute error is 0.02, that is, 2 percentage points of moisture content. For the *Eucalyptus* twig data, the corresponding error was just 1 percentage point. The poorer fit of the buttongrass data could result from several causes: the sampling interval was longer, the data are fragmented, and the data are spread over several

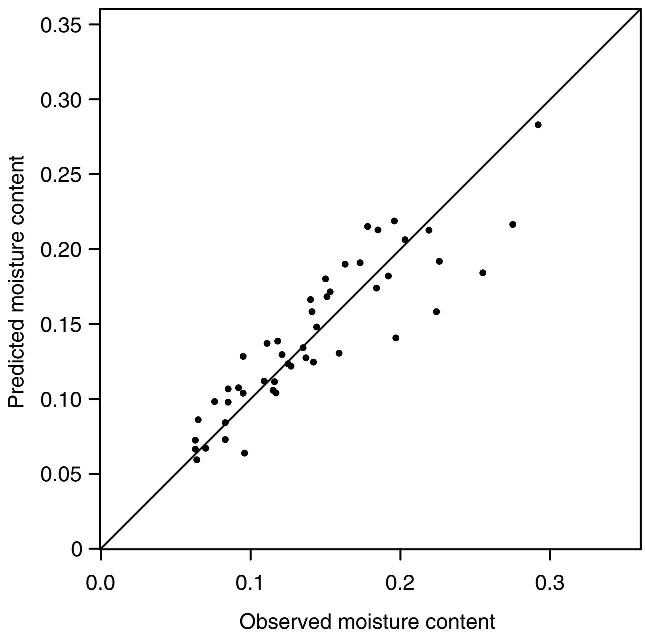

Fig. 7. Predicted versus observed moisture content for buttongrass moorland data (all four runs), using the DE method with Nelson's model for EMC.

seasons. In fact, considering these limitations in the data, our method performs quite creditably.

We have fitted Nelson's EMC model to the laboratory data for *Poa cæspitosa* tussock grass given in King and Linton (1963). The a and b values, calculated separately for adsorbing and desorbing conditions, are shown in Table 2. Our values for buttongrass agree quite well.

Discussion

We have proposed a new method for predicting fuel moisture content, which can be calibrated from field data, and which is more widely applicable than the methods of Viney (Viney and Catchpole 1991; Viney 1992). We have tested this method on data from Viney and Hatton (1989) that satisfy the conditions necessary for Viney's methods, and have found the estimates of fuel response time to be in good agreement. We have then applied the method to mallee and buttongrass data, neither of which satisfy Viney's conditions, and have found the method to perform well in predicting fuel moisture content.

We have found that spline interpolation of the hourly EMC values is unnecessary. The piecewise-constant approximation (7) gives almost identical answers, and is applicable to data (e.g. our buttongrass data) on which spline interpolation cannot be used.

The method can be used to estimate the EMC, as well as predicting fuel moisture content, by fitting Nelson's model (Nelson 1984). As Nelson found the parameters a and b in equation (9) to be fuel-dependent, for each new fuel we need to obtain moisture content data for runs of several days in order to calibrate the model.

For simplicity we have used the same equations for adsorption and desorption, but the method can easily be generalised so that different constants a and b are used for the desorption and adsorption phases. For example, we can fit the mallee aerial fuel data using the values for the regression constants a and b found by Nelson (1984) for southern red oak, which were close to the a and b we obtained. This produces an estimated response time of 3.23 h (s.e. 0.53 h), with MAE $= 0.012$ and RMSE $= 0.016$, which is not as good a fit as with our model. Note also that the estimate of response time has decreased from 3.8 h to 3.2 h. This is because of the hysteresis in the adsorption/desorption curve, which causes an inherent lag of EMC behind the instantaneous temperature and relative humidity (see Appendix). In principle it should be possible to estimate values of a and b separately for adsorption and desorption from the field data but, because the effect of hysteresis is similar to that of response time (in producing a time lag), there are practical difficulties in estimating the parameters. For our data sets this approach gave unrealistic estimates of a and b, with large standard errors. Longer data sets should work better.

We have made the assumption that the response time is constant for any given fuel. The equations used to estimate moisture content in the Canadian Forest Fire Weather Index System (Van Wagner 1987) assume that the response time depends on temperature, humidity and windspeed. This could be incorporated into the model by assuming some functional dependence on these quantities. We have also ignored differences in τ between adsorption and desorption (Anderson 1990*a*).

The two empirical coefficients in Byram and Jemison's equations for fuel-level temperature and humidity were developed for hardwood leaf litter. As far as we are aware they have never been calibrated for other fuel types, but were tested and found inaccurate for *Eucalyptus globulus* leaves in Chapter 6 of Viney (1992). Viney (1992) also points out that Byram and Jemison's model neglects several potentially important effects, such as overnight radiative cooling and daytime specific humidity variation near ground level. Incorporating such refinements could be expected to increase the accuracy of the fuel moisture content predictions, but should have comparatively little effect on the estimation of response time.

To use our model for predicting fuel moisture content, we need to know the fuel EMC. This can be predicted from fuel temperature and fuel-level relative humidity, as we have shown using Nelson's model. These, in turn, can be predicted from screen-level temperature and relative humidity, fuel-level windspeed, and solar radiation. For operational use for prediction some hours ahead, these quantities would need to be modelled and predicted.

The governing differential equation (1) is based on the assumption that the diffusion rate within the fuel is rapid compared with the transfer rate between the fuel and the atmosphere, and so is applicable to fine fuels with small response times. But in practice (1) is also used for fuels with longer response times, including litter beds (Van Wagner 1987). For such fuels, our model could be used on a daily basis rather than an hourly basis.

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Appendix. Hysteresis and time lag

Consider a fuel which responds instantaneously to changes in EMC, i.e. has zero time lag. Figure A1 shows, in a stylised form, the daily variation of EMC. Note that there are two EMC curves, shown dashed in the figure, one for adsorption and one for desorption. The fuel moisture content follows the appropriate EMC exactly, since there is no time lag, as shown in the figure (solid curve). The minima of both EMC curves occur at 2 pm in this illustration, so that both curves have a phase shift of 14 h with respect to midnight. The fuel moisture curve, though, has a phase shift of about 16.6 h, and so has an effective lag of 2.6 h behind the EMC curves. (The size of the time lag has been exaggerated somewhat for clarity in the figure.) Note that this lag is caused entirely by hysteresis.

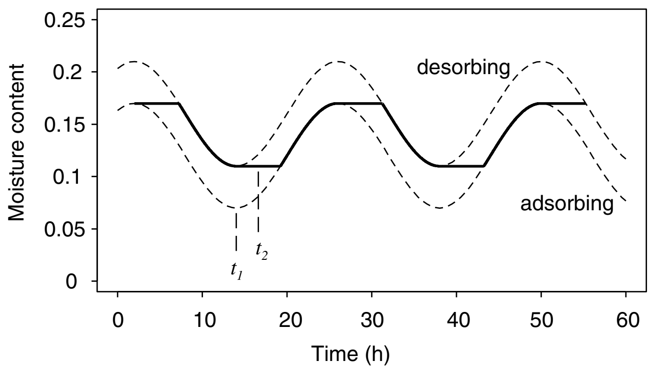

Fig. A1. Stylised EMC curves (dashed lines) for adsorption and desorption, and the corresponding fuel moisture curve (solid line). Here $t_1 = 14$ and $t_2 = 16.6$.