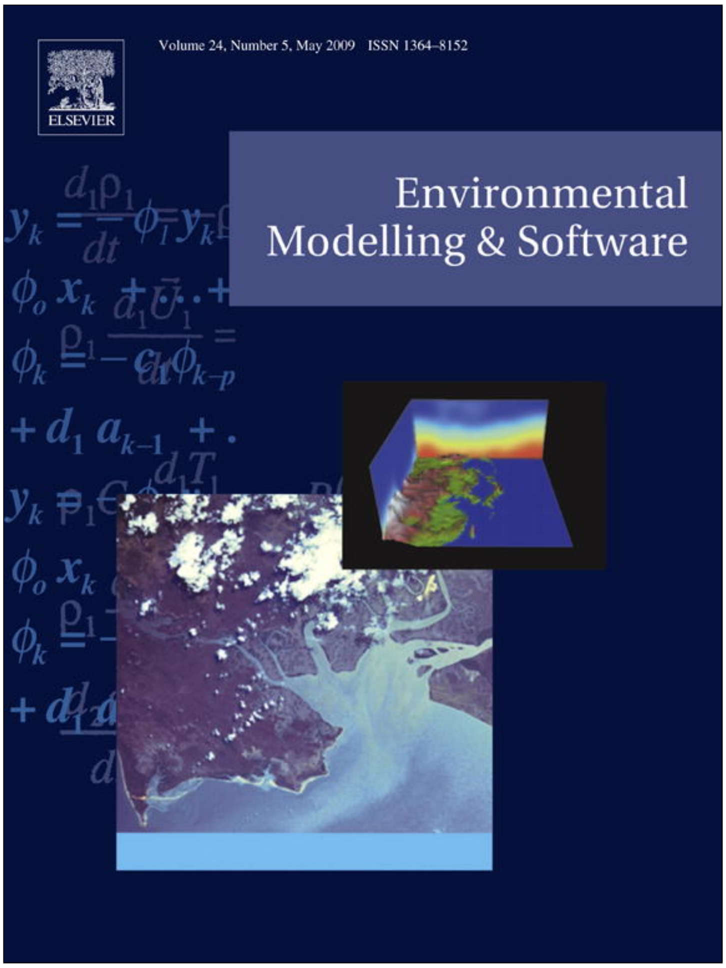
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A simple index for assessing fuel moisture content

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ABSTRACT

Assessing fuel moisture content to within a reasonable degree of accuracy is an important part of wildland fire management. In this paper we introduce a fuel moisture index that provides a simple and intuitive method for assessing fuel moisture content. The method can be quickly and easily applied in a field setting to provide a dimensionless measure of fuel moisture content. We compare the index with predictions from several models for fuel moisture content and conclude that it provides an equivalent measure of fuel moisture content for a number of fuel types. We go on to briefly discuss how the index could be used to construct a simple and intuitive fire danger index.

1. Introduction

The amount of moisture present in fuels is a key factor affecting fire potential and fire behaviour. Assessing fuel moisture content is therefore an important consideration in fire management practices, such as prescribed burning, where fire behaviour within certain thresholds is desired. When fuel moisture content is too high, ignition efforts will be in vain, while if fuel moisture content is too low, fires that are designed to be controlled can develop into uncontrollable fires that do more harm than good. An effective means of estimating fuel moisture content to within a reasonable degree of accuracy is thus an essential tool for fire management.

The moisture content of a fuel sample is defined as the relative mass of moisture in the sample when compared with the oven-dried mass of the fuel sample, and is expressed as a percentage. Fuel moisture content can change in response to various physical processes including latent heat effects, vapour exchange and rainfall (Viney, 1991; Nelson, 2000). Models designed to account for vapour exchange processes typically invoke the concept of equilibrium moisture content, which is the moisture content a fuel element will attain when subject for a sufficiently long time to specific environmental conditions. 'Environmental conditions' is usually taken to mean the ambient dry-bulb temperature and relative humidity surrounding the fuel element, though modelling efforts tend to employ nearby measurements of temperature and relative humidity, e.g. at screen height.

Models developed to describe fuel moisture content are often expressed as complicated mathematical formulae involving temperature and relative humidity, which are useful in computational applications but are seldom used directly by fire-fighting personnel on an actual fire-ground. Instead fuel moisture tables, which summarize the content of the mathematical formulae in a form that can be implemented in the field, are used to assess fuel moisture conditions. To ensure that such tables are used effectively it is desirable that they be simple to implement and easily understood by all that could potentially be required to use them. Thus, while there are effective tables and methods for estimating fuel moisture content currently in use, it is worth pursuing methods that are more simple and intuitive. Indeed, in many circumstances, instead of using the tables, fire fighters resort to intuition or employ simple tests such as the 'leaf test' (Tasmanian Forestry Commission, 1984; Burrows, 1984; Weber, 1990) to gauge fuel moisture content. While field equipment like the TH Fuel Moisture Meter (Wittronics Pty. Ltd., Australia) permits reasonably quick and accurate estimation of the moisture content of fuels in the field, such equipment is not always available to those in need of such information.

In this paper we discuss a simple, intuitive way to assess fuel moisture content. The fuel moisture index we introduce is calculated

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using measurements of dry-bulb temperature and relative humidity. This information can be readily obtained from a Kestrel weather meter (Nielsen–Kellerman, USA), for example, which is relatively inexpensive and now often part of the standard equipment on operational fire-fighting vehicles. Once temperature and relative humidity are known the fuel moisture index can be calculated easily using mental arithmetic. This means that the index could be quickly and easily applied to assess fuel moisture content in the field, for example, where it would have an advantage over more unwieldy methods. The simplicity and intuitive nature of the index also means that it would have a pedagogical advantage over more elaborate methods.

We demonstrate the utility of the fuel moisture index by comparing it to predictions from a number of fuel moisture content models that feature in the literature. We begin by giving a brief account of the fuel moisture content models that will be used for comparison in later sections.

2. Models of fuel moisture content

Viney (1991) provides an excellent review of several approaches to modelling the fuel moisture content of fine, dead fuels. In this paper we focus on those models that can be expressed as functional relationships involving dry-bulb temperature and relative humidity. In particular, these include all the equilibrium moisture content models described in Section 3 of Viney (1991) and the analytical model derived in Appendix A of Viney (1991), which accurately reproduces the tabulated fuel moisture content data in McArthur (1967). All of the models pertain to fine, dead fuels such as pine needles or eucalypt litter.

It should be pointed out that there are more recent models for estimating fuel moisture content that apply to a range of fuel size classes by explicitly accounting for the physical processes of fuel moisture exchange (e.g. Nelson, 2000). However, these models do not permit a direct comparison based on temperature and relative humidity data alone. The model described in Nelson (2000), for example, requires additional knowledge of solar radiation and rainfall, and fuel moisture contents are derived via an iterative scheme, rather than direct evaluation of a particular function. For these reasons, we will not consider models such as that described in Nelson (2000). Comparing the simple method proposed here with more physically based models will be the subject of further work. The fact that there exist more physically based models for fuel moisture content does not imply that the models considered here are not relevant. Indeed, as discussed below, two of the models considered here are employed in current methods for estimating fire danger rating (Goodrick, 2002; Matthews, in press).

For the sake of completeness we include a brief description of each of the models used in the ensuing comparisons. Implicit in the use of these models are the assumptions that the notional fuels are at the equilibrium moisture content attained through desorption (zero time-lag fuels) and that the models provide accurate predictions of fuel moisture content for the relevant fuel type. More information on the models can be found in Viney (1991). In the following we use T to denote dry-bulb temperature, measured in $^\circ$C, and H to denote relative humidity, measured in %.

2.1. Simard (1968)

Regression analysis of data pertaining to the equilibrium moisture content of wood yielded the following expression for equilibrium moisture content E (Simard, 1968)

$$E = \begin{cases} 0.03 + 0.2626H - 0.00104HT, & H < 10 \\ 1.76 + 0.1601H - 0.0266T, & 10 \le H < 50 \\ 21.06 - 0.4944H + 0.005565H^2 - 0.00063HT, & H \ge 50 \end{cases} \quad (1)$$

It should be noted that Eq. (1) forms the basis for the moisture damping coefficient in Fosberg's Fire Weather Index (Fosberg, 1978; Goodrick, 2002), which is an index that relates to fire behaviour potential.

2.2. Anderson et al. (1978)

Based on a model of Van Wagner (1972), Anderson et al. (1978) used *Pinus ponderosa* needles and a regression analysis to obtain the following model for equilibrium fuel moisture content achieved through desorption.

$$E = 1.651H^{0.493} + 0.001972\exp(0.092H) + 0.101(23.9 - T) \quad (2)$$

An expression for the equilibrium moisture content achieved through adsorption was also derived in Anderson et al. (1978), but this will not be considered here. As pointed out by Viney (1991), equilibrium fuel moisture contents achieved by desorption are typically 2% higher than those achieved through adsorption.

2.3. Nelson (1984)

Nelson (1984) derived a semi-physical model for equilibrium moisture content based on thermodynamics and empirical data. The resulting expression is

$$E = c_1\left(c_2 - \ln\left((273.15 + T)\ln\frac{100}{H}\right)\right). \quad (3)$$

In Eq. (3) the constants c_1 and c_2 need to be determined through regression techniques by appealing to data relating equilibrium moisture content to relative humidity. However, the two constants c_1 and c_2 merely 'scale' and 'shift' the values of E given by Eq. (3) and will therefore be unimportant in the methods of comparison employed in the following sections. Hence, for convenience we fix their values as $c_1 = 10$ and $c_2 = 7$. These values of c_1 and c_2 bring the values of E given by Eq. (3) into a range that is comparable to the ranges of E given by the other models considered in this study. Nelson (1984) also suggests that Eq. (3) is only valid for relative humidities between 10% and 90%.

2.4. Van Wagner and Pickett (1985)

Van Wagner and Pickett (1985) built on the model of Van Wagner (1972) to include a term which ensured that the model produced equilibrium fuel moisture contents that were approximately zero whenever relative humidity was zero. The resulting expression for equilibrium fuel moisture content achieved through desorption is

$$E = 0.942H^{0.679} + 0.000499\exp(0.1H) + 0.18(21.1 - T)(1 - \exp(-0.115H)). \quad (4)$$

Van Wagner and Pickett (1985) also derive an expression for the equilibrium moisture content achieved through adsorption but this will not be considered in the present study.

2.5. Viney (1991)

The relationship between air temperature, relative humidity and the moisture content of the surface layer of eucalypt litter was presented in tabular form in Table 1 of McArthur (1967). Viney

(1991) used an advanced regression analysis of the data contained in the table to derive the following equation for the moisture content of eucalypt litter m

$$m = 5.658 + 0.04651H + 3.151 \times 10^{-4}H^3T^{-1} - 0.1854T^{0.77}. \quad (5)$$

Eq. (5) provides excellent agreement with the tabulated relationship in McArthur (1967). Viney (1991) points out that, due to its nonlinearity, Eq. (1) is only strictly applicable to temperatures in the range of 10–41 °C and relative humidities in the range of 5–70% that satisfy the linear constraint

$$42.5 - 1.25T < H < 94.5 - 1.35T.$$

It is of interest to note that m, given by Eq. (5), can be used to estimate the McArthur Mark 5 Forest Fire Danger Index (FFDI) as (Noble et al., 1980; Matthews, in press):

$$\mathrm{FFDI} = 33.78D\exp(0.0234U)m^{-2.1},$$

where U is wind speed and D is the drought factor, which provides a measure of the amount of fuel available for combustion. Note that the equation for FFDI above provides values that are approximately equal to those provided by the equation found in Noble et al. (1980) and in Sharples et al. (in press). For the details of how the approximate equation for FFDI is obtained the reader is referred to Matthews (in press).

3. A simple index for fuel moisture

The models given by Eqs. (1)–(5) all provide an optimal fit to the respective data sets that they were trained on. Intuitively, however, they are not easy to interpret. Relationships like those considered in Pook (1993) and Pook and Gill (1993) for *Pinus radiata* fine fuels, on the other hand, are much more intuitively amenable. In particular Pook and Gill (1993) consider relationships of the form

$$\mathrm{FFM} = a + bH - cT, \quad (6)$$

where FFM is the fine fuel moisture content and a, b and c are positive parameters. Eq. (6) embodies the intuitive notion that hotter and drier air corresponds to lower fuel moisture contents. Models like those represented by Eq. (6) ignore the nonlinear and interaction effects that are found in Eqs. (1)–(5) but it has been suggested by one of the authors (A.M. Gill) that an equation like (6) can be taken as a simple 'rule of thumb', or field method for estimating dead, fine fuel moisture content using mental arithmetic and inputs of air temperature and relative humidity only.

We therefore consider a simple fuel moisture index (after Pook, 1993; Pook and Gill, 1993) that we define as a function of dry-bulb temperature and relative humidity as

$$\mathrm{FMI} = 10 - 0.25(T - H). \quad (7)$$

With reference to Eq. (6), we have chosen the parameters $a = 10$ and $b = c = 0.25$ to allow easy computation of the FMI while ensuring that a positive number, which decreases as conditions become increasingly hotter and drier, is obtained.

FMI is a dimensionless index and should not be considered as giving a direct estimate of fuel moisture content, as such. However, a question of principal interest is how the variable FMI relates to fuel moisture content as given by Eqs. (1)–(5). This question is addressed in the following sections.

4. Data and methods

To facilitate the comparison of FMI, Eq. (7), with the fuel moisture contents given by the models (1)–(5) we used data recorded by the Bureau of Meteorology's automatic weather station located at Canberra Airport in the Australian Capital Territory (Station ID: 070014, Long.: 149.20, Lat.: −35.30, Elev.: 578.4 m). In particular, we use half-hourly data recorded between 00:00AEST, 1st November 2006 and 23:30AEST, 31st March 2007, inclusive. The period covered by the data comprises a large majority of the 2006/2007 fire season and therefore includes a broad range of temperature and relative humidity values relevant to fire weather and fuel moisture considerations. Specifically, temperature ranged from 1.7 °C to 39.9 °C and relative humidity ranged from 8% to 99%.

In the ensuing comparison we only considered those data that had values for both dry-bulb temperature and relative humidity. This gave a total of 7231 pairs of temperature and relative humidity data with which to calculate FMI and the fuel moisture contents given by the five models, Eqs. (1)–(5). Due to the constraints that apply for some of the models the number of points ultimately used in the comparisons differed across the five models. The number of points used in the comparison for each model can be seen in Table 1. Of particular note is the proportion (approx. 40%) of data that cannot be used in Viney's model (5).

Comparisons between the predictions of the five models and FMI were made by calculating FMI and the predictions of the relevant model at each of the valid data points, the quantity of which are contained in Table 1. Scatter plots of the model predictions versus FMI were created and correlation and error statistics arising from generalised regression analyses were calculated. Rank correlation statistics were also calculated to test the compatibility of the respective scales of FMI and the model predictions.

5. Results

Scatter plots of each of the five model predictions versus the corresponding FMI values can be seen in Fig. 1. Note that the gap in the data in Fig. 1(a) is due to a discontinuity in Eq. (1). In each of the five cases a nonlinear relationship between FMI and the model predictions is evident. In all cases the relationships are monotonic increasing over the data range and are near linear for fuel moisture values in the drier part of the data range.

The nonlinear relationship in each of the five cases was approximated using polynomial regression techniques that produced a curve of best fit for each of the data sets. The relationship between Simard's model, Eq. (1), and FMI was characterised by a fourth-order polynomial (Fig. 1(a)). The same was true for the relationship between Nelson's model, Eq. (3), and FMI (Fig. 1(c)) and for the relationship between Van Wagner and Pickett's model, Eq. (4), and FMI (Fig. 1(d)). The relationship of Anderson et al.'s model, Eq. (2), with FMI (Fig. 1(b)) and the relationship between Viney's model, Eq. (5), and FMI (Fig. 1(e)) were both characterised by fifth-order polynomials. Note that the degree of polynomial used to quantify the relationships is largely irrelevant. Indeed, similar curves could be attained by hand-drawing curves of best fit. Polynomial regression simply provides a convenient way of quantifying the relationship. Using a fourth-order polynomial, instead of a fifth-order polynomial, to quantify the relationship between the FMI and the models of Viney and Anderson et al. only changed the correlation statistics by 0.0001. A fourth-order polynomial was not used for these model comparisons because the resultant curves possessed an upward trend for small FMI values that obviously (visually) did a poorer job of quantifying the relationship for those values.

The correlation and error statistics arising from the regression analyses can be seen in Table 1. The correlation coefficients are all

Table 1
Number of points used in the comparisons and the correlation and error statistics arising from the regression analyses for each of the five models.

Model	No. of data points used in comparison	Correlation	Mean absolute error (%)	Max. absolute error (%)	Rank correlation
Simard	7231	0.988	0.58	4.20	0.992
Anderson et al.	7231	0.987	0.44	6.49	0.997
Nelson	6892	0.987	0.94	6.32	0.990
Van Wagner and Pickett	7231	0.997	0.23	3.79	0.999
Viney	4277	0.999	0.08	1.21	1.000

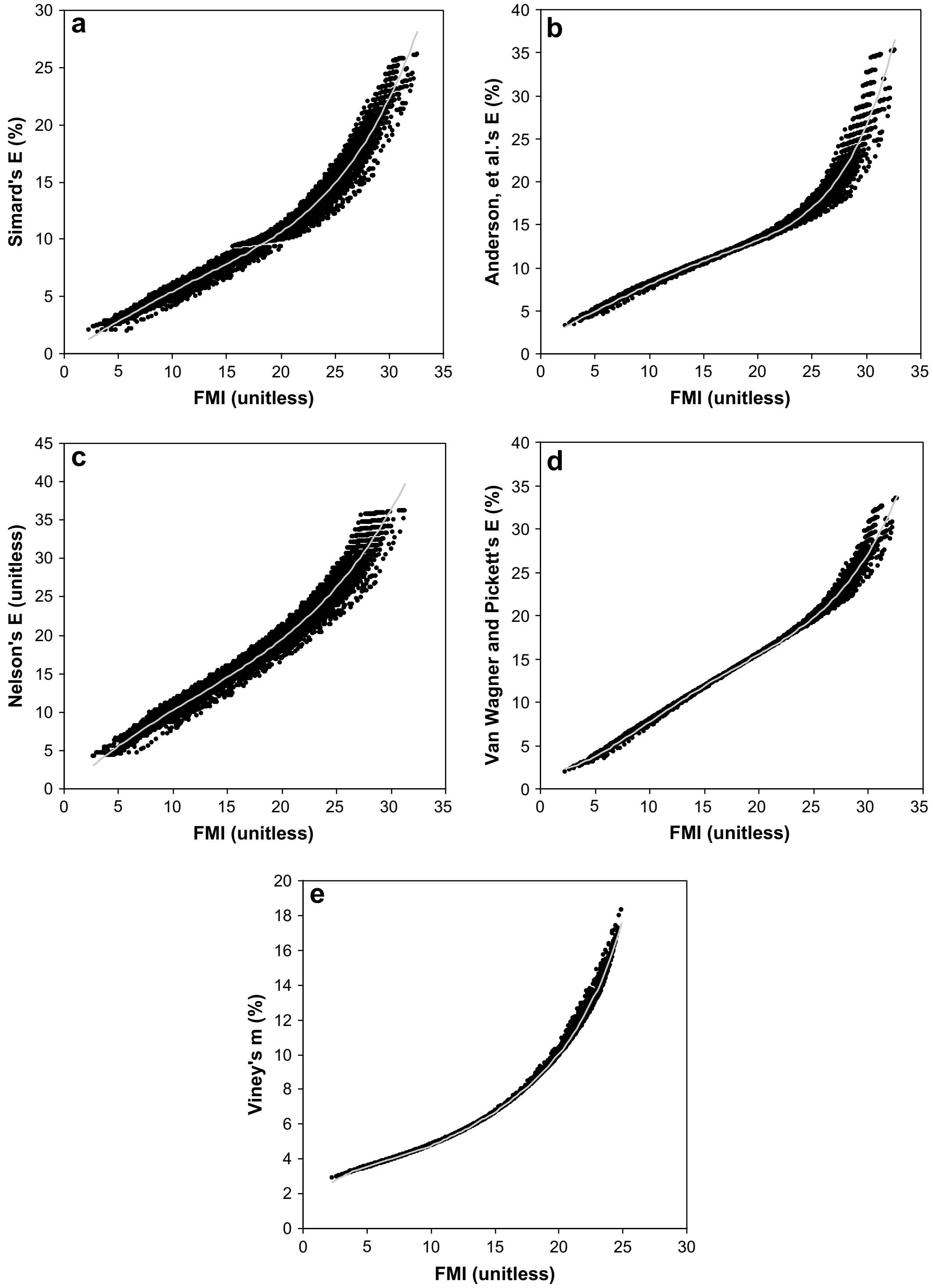

Fig. 1. Scatter plots of the various fuel moisture model predictions versus FMI. (a) Simard's model, Eq. (1), (b) Anderson et al.'s model, Eq. (2), (c) Nelson's model, Eq. (3), (d) Van Wagner and Pickett's model, Eq. (4), (e) Viney's model, Eq. (5). The grey line in each plot is the curve fitted using polynomial regression techniques.

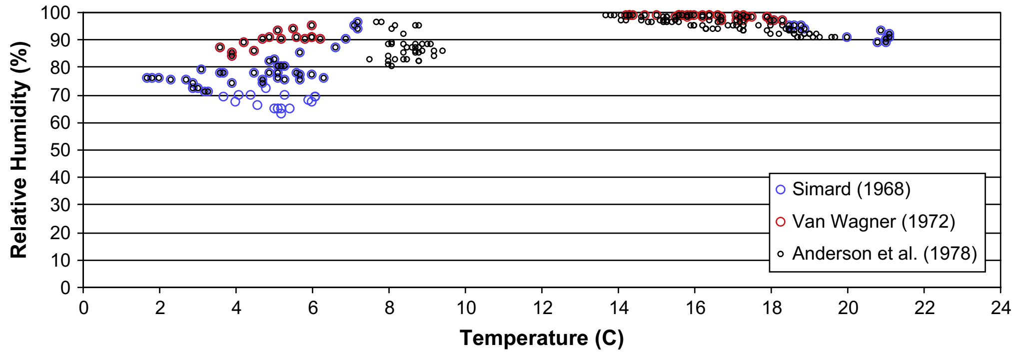

Fig. 2. Plot showing the relationship between values of temperature and relative humidity corresponding to instances when the absolute difference between the model predictions and that given by the fitted function of FMI is greater than 2.5%.

very close to unity and the mean absolute errors are all less than 1%. The maximum absolute errors vary from just over 1% for the Viney (1991) model up to approximately 6.5% for the model of Anderson et al. (1978). The larger errors in the model of Anderson et al. (1978) occur only when fuel moisture is high. For example, the maximum absolute error, for the Anderson et al. (1978) model, of 6.49% occurs when the temperature is 3.6 °C and when relative humidity is 87%. Obtaining accurate fuel moisture measurements under these types of conditions is not generally going to be crucial, particularly in the context of fire management. The same is generally true for the other models also, with maximum absolute errors corresponding to low temperatures and/or high relative humidity. This fact is illustrated for the models of Simard (1968), Van Wagner (1972) and Anderson et al. (1978) in Fig. 2. The maximum absolute error of 1.21% obtained for the model of Viney (1991) is an exception, occurring when temperature was 10.1 °C and relative humidity was 62%. However, recall that the model of Viney (1991) required $T \geq 10$ °C and $H \leq 70\%$. In any case an error of 1.21% is of no great concern.

The correlation and error statistics, and observance of Fig. 1, suggest that FMI is a reliable predictor of the fuel moisture content values derived from the five models (1)–(5). In fact, up to a small error, the FMI shows a unique correspondence with the model predictions, which indicates that FMI gives a measure of fuel moisture content that is equivalent to that provided by the models considered. The only difference is one of scale. This suggests that, in the context of fuel moisture content, FMI is a unifying variable. For this to be clearly the case, the differences in scale need to be consistent across the different models that pertain to different fuel types. To check the consistency in these differences in scale we

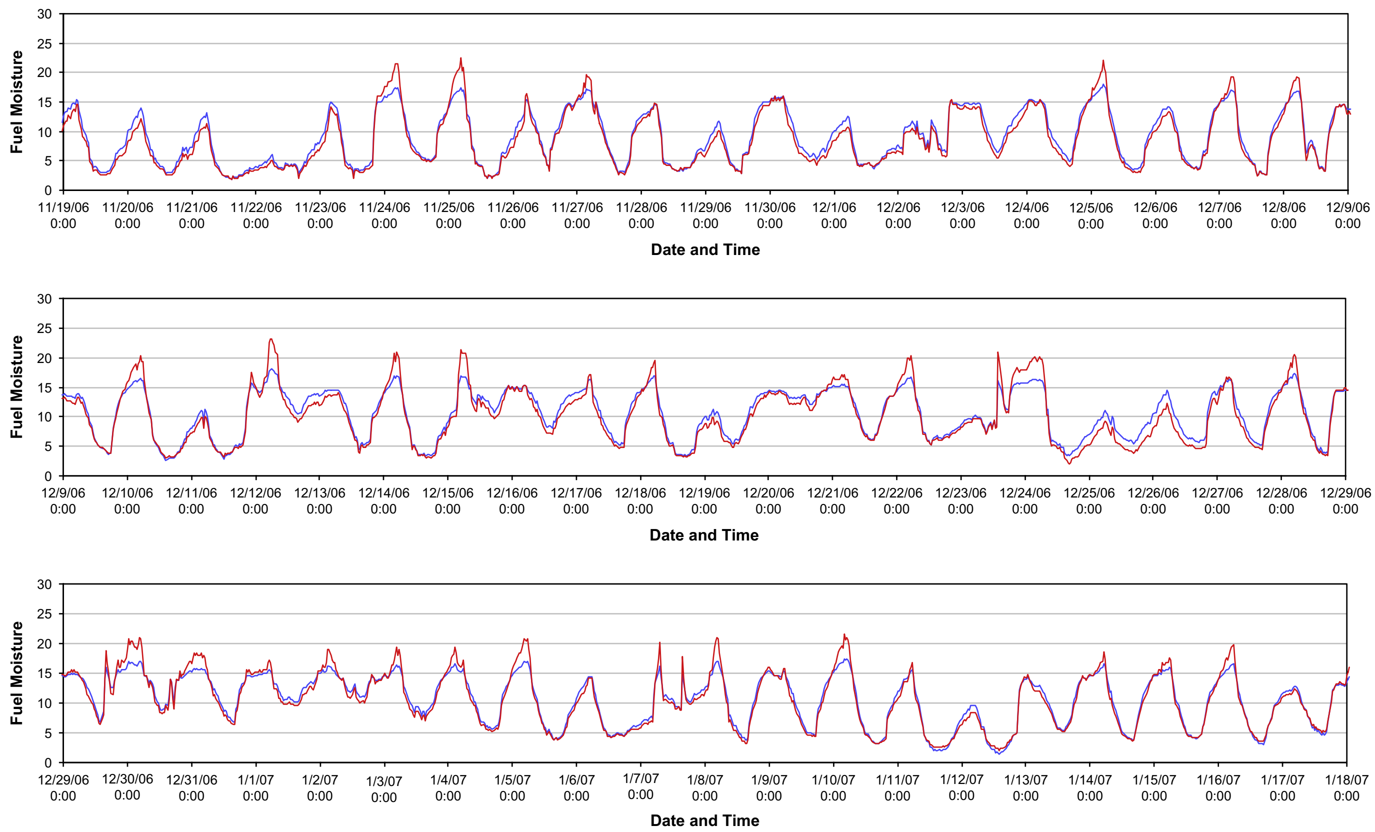

Fig. 3. Time series plots of FMI (blue line) and fuel moisture content values (red line) derived from the model of Simard (1968). The FMI values have been multiplied by a calibration factor so that the means of the two time series are equal. The three panels show consecutive 20 day periods from 00:00 AEST, 19th November 2006–00:00 AEST, 18th January 2007.

calculated rank correlations for FMI and each of the model predictions. The resultant rank correlations, rounded to three decimal places, can be seen in Table 1. All of the rank correlations are 0.990 or larger, which means that the FMI scale and the fuel moisture content scales arising from each of the five models are consistent. This implies that FMI provides an equivalent measure of fuel moisture content when compared to model predictions pertaining to a number of different fuel types.

This fact is further exemplified in Fig. 3, which shows time series of the FMI and fuel moisture content derived from Simard's model (1), and Fig. 4, which shows time series of FMI and fuel moisture contents derived from Viney's model (5). To better facilitate comparison, and for this reason only, the FMI in Figs. 3 and 4 has been multiplied by a (calibration) constant so that the average of the modified FMI values equals the average of the fuel moisture content predictions derived from models (1) and (5), respectively. As such Figs. 3 and 4 demonstrate that the FMI displays the same quantitative behaviour as the predictions of the models of Simard and Viney, respectively.

It is worth noting that when compared with FMI, the quantity $T-H$ would provide an even simpler, yet equally valid measure of fuel moisture content. Traditionally, however, all indices encountered in fire related matters are positive, presumably for conceptual or psychological reasons. So as not to break with this tradition, we have used the positive valued FMI rather than $T-H$, which will often be negative.

6. Discussion and conclusions

The relationship between the fuel moisture index (FMI) introduced in this paper and fuel moisture predictions derived from five different fuel moisture content models was found to be one-to-one (up to a small error) in each of the cases. In fact, as can be seen in Fig. 1, for the drier end of the fuel moisture spectrum, the relationship between FMI and the predictions of the five models was near linear. This means that to within a reasonable degree of accuracy, the FMI values correspond uniquely, and linearly for small values of the FMI, to values derived from the five models for fuel moisture content. Therefore, assuming that each of the models adequately predicts actual fuel moisture content, we can conclude that the FMI provides an equivalent measure of actual fuel moisture content that is intuitive and easy to calculate. Nonlinear correlations between FMI and the predictions of the fuel moisture content models considered were all greater than 0.98 and the mean absolute errors all less than 1%. The equivalence of FMI to modelled fuel moisture content was found to be valid for a number of models that pertain to different fuel types including wood, pine needles and eucalypt litter. The index embodies the intuitive notion that when temperature is high and relative humidity is low, fuel moisture content is expected to be relatively low, while if temperature is low and relative humidity is high, fuel moisture content is expected to be relatively high. In essence this is a simplified way of looking at the vapour exchange process; under hot, dry conditions fuel will give moisture up to the air, while under cool, moist conditions the exchange will tend to be in the other direction, provided that the fuel is below its fibre saturation level.

The index can be easily calculated using mental arithmetic. For example, if temperature and relative humidity are measured to be 34 °C and 22%, respectively, then FMI is calculated by subtracting 22 from 34 to get 12, dividing by 4 to get 3 and then subtracting from 10 to get FMI = 7. It is important to note that this does not imply an actual fuel moisture content of 7%. If an estimate of actual fuel

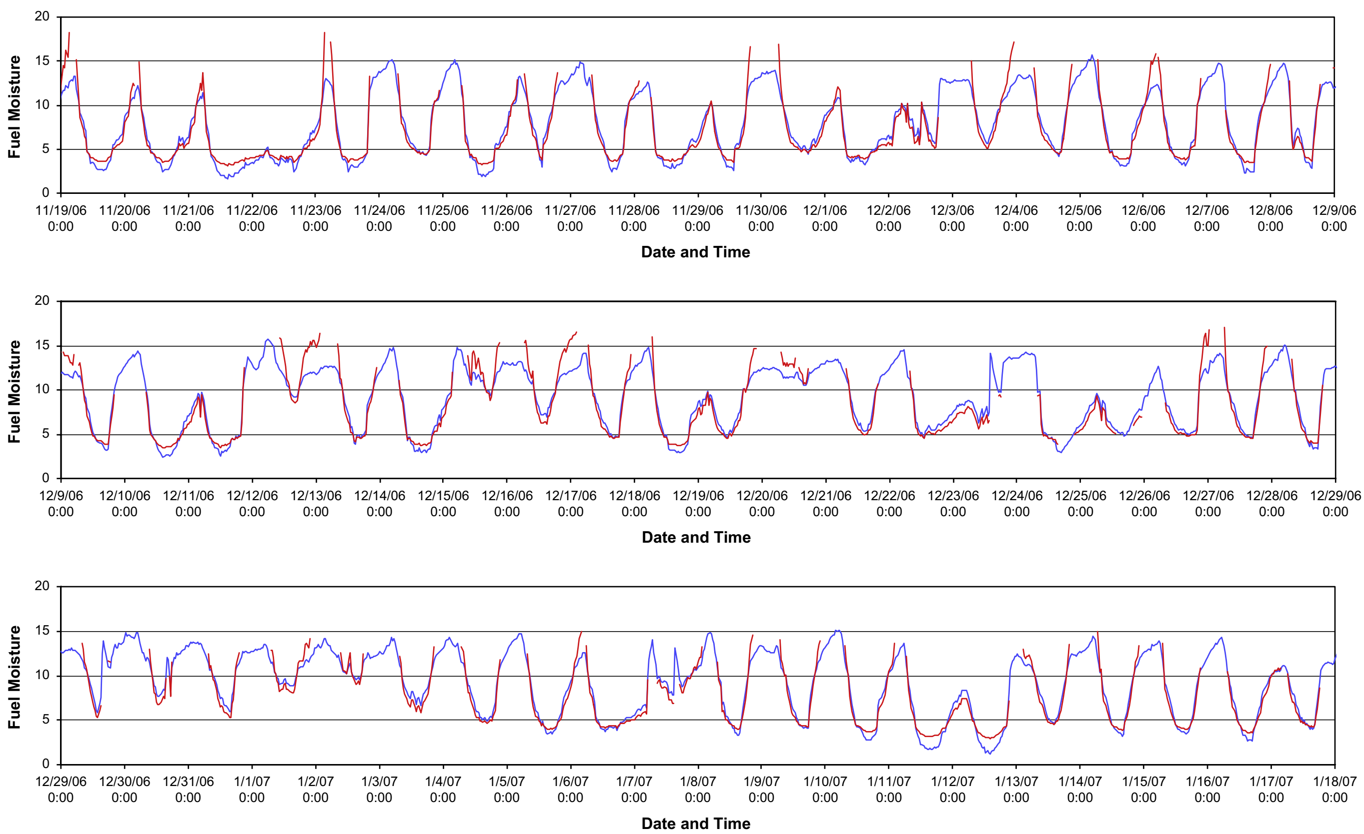

Fig. 4. Time series plots of FMI (blue line) and fuel moisture content values (red line) derived from the model of Viney (1991). The FMI values have been multiplied by a calibration factor so that the means of the two time series are equal. The three panels show consecutive 20 day periods from 00:00 AEST, 19th November 2006–00:00 AEST, 18th January 2007. Note that the gaps in the predictions of Viney's model are due to the constraints on the applicable temperature and relative humidity values discussed in Section 2.5.

Table 2
Correlation and error statistics arising from the analyses using FMI_c with various values of c for the models of Viney and Simard.

c	Viney			Simard		
	Correlation	Mean absolute error (%)	Max. absolute error (%)	Correlation	Mean absolute error (%)	Max. absolute error (%)
0.5	0.995	0.242	1.305	0.961	1.045	7.056
1.0	0.998	0.114	1.477	0.988	0.576	4.258
1.5	0.995	0.211	1.912	0.995	0.386	2.486
2.0	0.990	0.309	2.444	0.997	0.272	2.374
2.5	0.988	0.337	2.620	0.998	0.315	3.023
3.0	0.985	0.376	3.034	0.999	0.178	1.122
3.5	0.983	0.407	3.068	0.999	0.150	1.410
4.0	0.981	0.452	2.885	0.999	0.141	0.775
4.5	0.980	0.434	3.262	0.999	0.122	1.193
5.0	0.979	0.444	3.318	0.999	0.155	0.746

moisture was desired then FMI could be converted, by means of a look-up table or equivalent curve, which is perhaps stuck on the back of the device used to measure temperature and relative humidity. In this case a fuel moisture content of approximately 4–6% would be obtained, depending on the fuel type. However, since the scales are equivalent it is possible to talk about fuel moisture in terms of the FMI alone, rather than in terms of percentage of actual moisture. Hence, once enough familiarity with the interpretation of the FMI, applied to a particular fuel type, has been gained, the use of tables or graphs would not be required; all that would be required is knowledge of the simple FMI formula. Using the index in this way would permit personnel on a fire-ground to assess fuel moisture content quickly and with reasonable accuracy in a field setting, where it would have an advantage over more unwieldy methods. This could assist in optimising the timing of ignition in prescribed burns, for example. Moreover, it has often been remarked that fire behaviour can become erratic when fuel moisture content falls below 5%; if fire behaviour is particularly sensitive to low fuel moisture contents then providing fire-fighting personnel with a simple way of tracking fuel moisture content would lead to improved safety procedures – extreme care may be needed when fighting fires at particularly low fuel moisture contents, or equivalently, when the FMI falls below some threshold value.

The FMI could also be used as the basis for a simplified fire danger index. Fire danger rating is essentially modelled by combining information on wind speed and fuel moisture content (e.g. Chandler et al., 1983). It therefore seems reasonable that the FMI, which can be taken as a surrogate for fuel moisture content, supplemented with wind speed information, could yield a simple

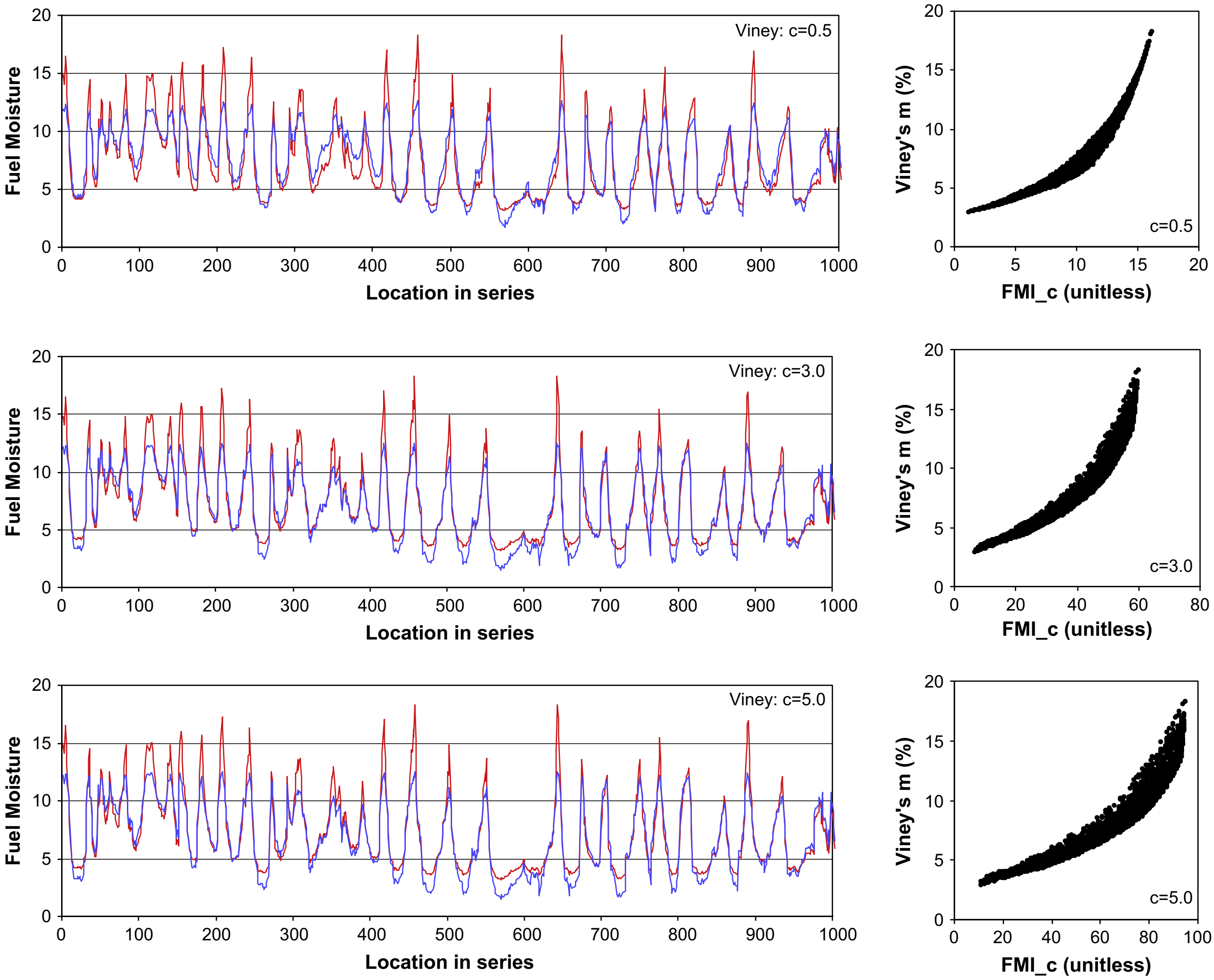

Fig. 5. Series plots of FMI_c (blue line) and fuel moisture content values (red line) derived from the model of Viney (1991). Only the first 1000 points in the series are shown. The FMI_c values have been multiplied by a calibration factor so that the means of the two series are equal. The top, middle and bottom panels show the results for $c = 0.5$, 3.0 and 5.0, respectively. The panels on the right show the corresponding scatterplots of the predictions from Viney's model against the (unscaled) FMI_c values.

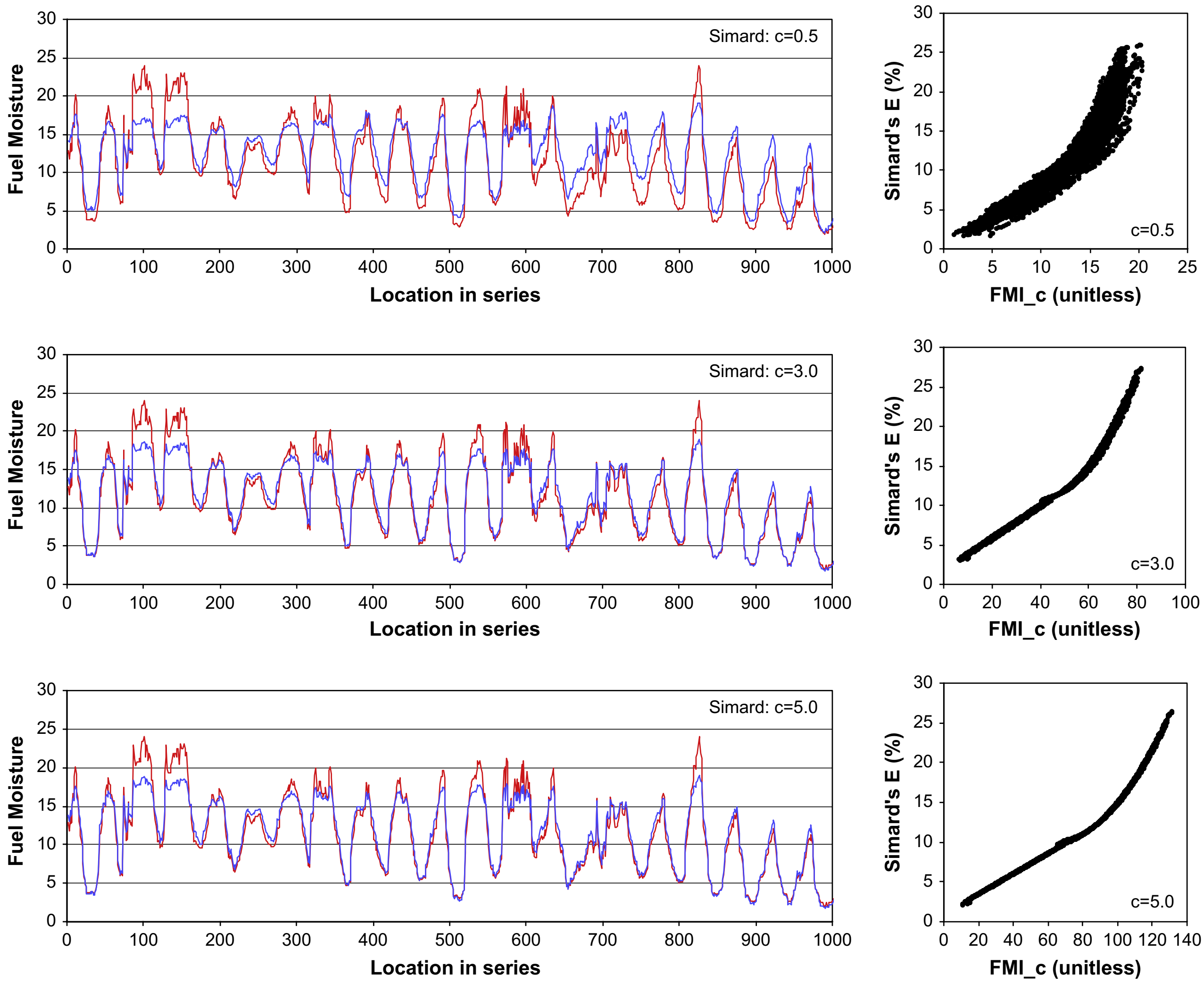

Fig. 6. Series plots of FMI_c (blue line) and fuel moisture content values (red line) derived from the model of Simard (1968). Only the first 1000 points in the series are shown. The FMI_c values have been multiplied by a calibration factor so that the means of the two series are equal. The top, middle and bottom panels show the results for $c = 0.5$, 3.0 and 5.0, respectively. The panels on the right show the corresponding scatterplots of the predictions from Simard's model against the (unscaled) FMI_c values.

measure of fire danger. A simple fire danger index, such as the one proposed, would not in general be related to fire behaviour or fire spread in a simple linear fashion, as is often found in other fire danger rating schemes, but could be a useful pedagogical tool that would also permit field assessment of fire danger levels without the need for tables of graphs. Such an index is developed and compared to existing models for fire danger rating in Sharples et al. (in press).

The fact that T and H have been given equal weighting in the expression for FMI deserves further explanation. Indeed, one could consider a fuel moisture index which contains a term of the form $T - cH$, for some constant c not equal to unity. That is,

$$FMI_c = 10 - 0.25(T - cH). \tag{8}$$

This possibility was examined using predictions of fuel moisture content derived from Viney's model and Simard's model. Table 2 shows the correlation and error statistics arising from using different values of c in FMI_c. Fig. 5 shows series plots of predictions from Viney's model and values of FMI_c that have been scaled so that the means of the two series agree. Also shown in Fig. 5 are scatterplots of Viney's model predictions against (unscaled) FMI_c values. Fig. 6 shows the same content for Simard's model. It was found that the optimal values of c varied widely for the two models. For the model of Viney (1991) $c \approx 1$, while $c \to \infty$ for the model of Simard (1968). Table 2 also indicates that the optimal values of c resulted in only a minimal increase in the correlation statistics and a relatively small decrease in the mean absolute errors. Figs. 5 and 6 show that FMI_c displays quantitative behaviour very similar to the model predictions regardless of the value of c. Inclusion of $c \neq 1$ in the expression for FMI therefore draws away from the universality of the index and makes it harder to calculate mentally, with only minimal advantage to be gained.

The effect of correlation between T and H was also briefly examined. The data set used in the above analyses (Canberra Airport)

Table 3
Correlation and error statistics arising from the analyses using FMI with synthetic uncorrelated data for the models of Viney and Simard.

Model	Correlation	Mean absolute error (%)	Max. absolute error (%)
Simard	0.963	0.590	2.225
Anderson et al.	0.993	0.229	1.302
Nelson	0.956	1.177	4.466
Van Wagner and Pickett	0.997	0.374	1.695
Viney	0.999	0.093	1.015

The correlation between temperature and relative humidity was 0.012.

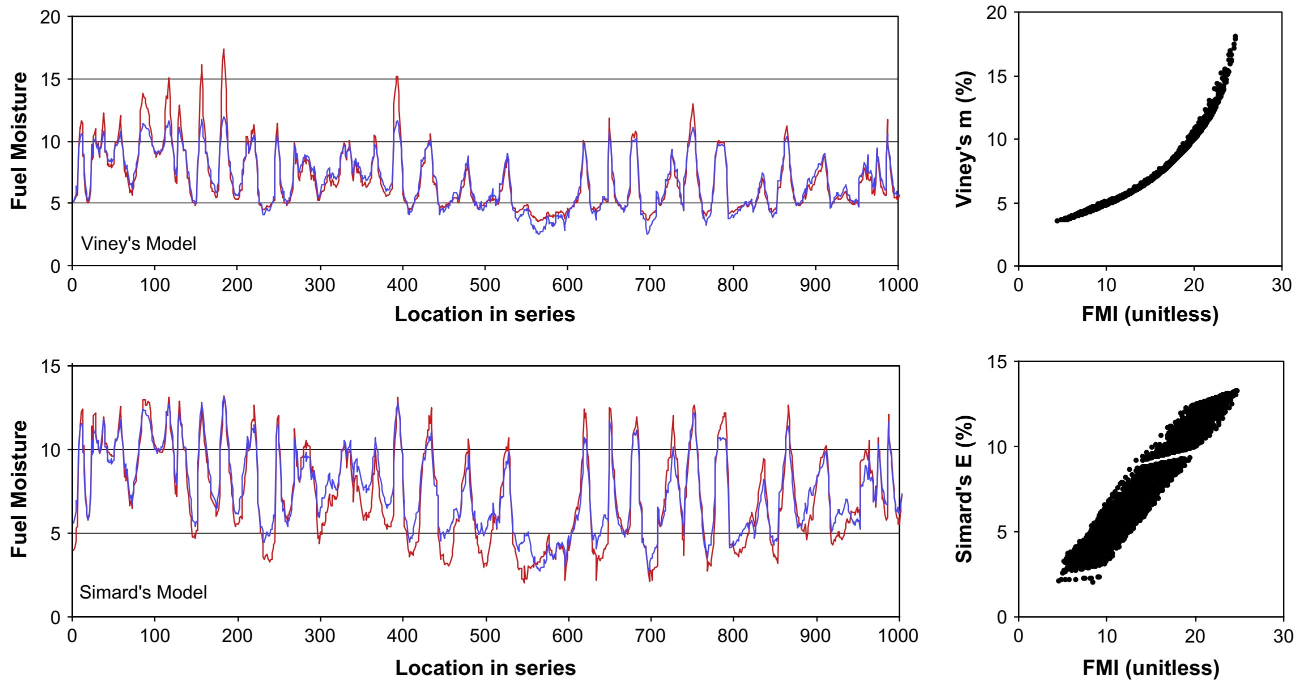

Fig. 7. Series plots of FMI (blue line) and fuel moisture content values (red line) derived from the models of Viney (top panel) and Simard (bottom panel) calculated using synthetic uncorrelated temperature and relative humidity data (correlation = 0.012). Only the first 1000 points in the series are shown. The FMI values have been multiplied by a calibration factor so that the means of the two time series are equal. The panels on the right show the corresponding scatterplots of the predictions from Viney's and Simard's models against the (unscaled) FMI values.

exhibited a correlation between T and H of -0.74. The results obtained from the Canberra Airport data set were compared with those obtained using synthetic temperature and relative humidity data, which was constructed to exhibit a near-zero correlation between T and H of 0.012. The results of the ensuing comparison can be seen in Table 3. The comparison showed only relatively minor changes in the resultant statistics, e.g. for the Viney (1991) model, analyses based on the synthetic data yielded a nonlinear correlation of 0.999, a mean absolute error of 0.09% and a maximum absolute error of 1.02%, all of which are similar to the statistics seen in Table 1. Larger absolute errors again occurred under relatively cool and wet conditions, which are unlikely to be important in the context of fire management. Fig. 7 suggests that the utility of the FMI is relatively insensitive to the correlation of the temperature and relative humidity data. This is especially true for the model of Viney (1991). Table 3 suggests that the statistics relating to the models of Simard and Nelson are the most sensitive to correlation between temperature and relative humidity. This is confirmed by the scatterplot of Simard's model predictions against FMI, seen in Fig. 7. Note that the synthetic data was constructed by amending the data set used for the comparison of FMI with the model of Viney (1991), and as such only contained data satisfying $T \geq 10\,^{\circ}\mathrm{C}$ and $H \leq 70\%$. This is the reason for the smaller maximum absolute errors seen in Table 3.

Although the FMI has been shown to accord well with the predictions of several fuel moisture content models, caution should be exercised when applying the method in the field. The methods employed in this study were largely theoretical and need to be supplemented by an empirical analysis involving actual fuel moisture content data for a number of different fuel types and fuel size classes. Use of an index that has not been substantiated empirically could potentially lead to incorrect assessment of fuel moisture contents and fire behaviour characteristics which could endanger the lives of fire fighters and the general public. However, regardless of what empirical fuel moisture data might reveal, the fact remains that the FMI will always provide a measure of fuel moisture content practically equivalent to that predicted by each of the five models considered.

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