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Stand-specific litter moisture content calibrations for the Canadian Fine Fuel Moisture Code

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Abstract. A large dataset of litter moisture measurements collected at several sites across Canada by the Canadian Forest Service over the period from 1939 to 1961 is analysed. The stands in which sampling was carried out were described by three main variables: forest type (pine, spruce, Douglas fir, mixedwood and deciduous), season (spring, summer and fall), and stand density (light, moderate and dense). All three variables were found to have a significant influence on the relationship between the Canadian Forest Fire Weather Index System's Fine Fuel Moisture Code (FFMC) and surface litter moisture. Moisture in the upper duff layer was also found to have a significant influence on the relationship between FFMC and litter moisture content, with a wetter duff layer leading to moister surface conditions than would be indicated by the FFMC value. A model for litter moisture is developed, which provides a method of adjusting the standard FFMC value for the influences of forest type, stand density, season and duff moisture content.

Additional keywords: Canadian Forest Fire Danger Rating System, duff moisture.

Introduction

The moisture content of fine fuels on the forest floor (e.g. needles, leaves, small twigs) has an important influence on the rate of spread and the sustainability of a surface fire. Models used operationally to predict forest fire behaviour such as the Rothermel model (Rothermel 1972), BEHAVE (Andrews 1986) in the US, and the Canadian Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992) in Canada rely on estimates of fuel moisture to predict both fire spread rate and the consumption of fuels. In the FBP System, fuel moisture is estimated from outputs of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987), and moisture content in the surface fuels along with wind speed are two of the main factors influencing the predicted rate of spread of a fire in any particular forest type. In addition, other research has shown that moisture content (as modelled by the FWI System fuel moisture codes) significantly influences the probability of both human- and lightning-caused fire occurrence in Canada (Martell *et al*. 1989; Poulin-Costello 1993; Vega-Garcia *et al*. 1995; Wotton *et al*. 2003; Wotton and Martell 2005).

The FWI System uses daily observations of temperature, relative humidity, wind speed and rainfall to estimate moisture in three layers of the forest floor: cured fine surface fuels are represented by the Fine Fuel Moisture Code (FFMC); the moisture in the upper organic layer is represented by the Duff Moisture Code (DMC); and the moisture of deep organic layers or large woody materials are represented by the Drought Code (DC). These three numerical fuel moisture codes are arranged such that they increase in value with increasing dryness; that is, a code value of 0 represents the full saturation of the layer with moisture. This inverted scale was developed for psychological effect, so that higher numbers indicate higher fire potential; however, at their core, the three moisture models of the FWI System work following a simple exponential model of moisture exchange. In these models, moisture content of each fuel layer moves towards an equilibrium value specific to the layer at some set rate; in the FFMC, both the equilibrium moisture content and the rate of drying (or wetting) are dependent on atmospheric conditions such as daily air temperature and relative humidity.

The moisture codes of the FWI System were developed to be representative of the moisture content of forest floor fuels in a mature, closed-canopy jack pine (*Pinus banksiana* Lamb.) or lodgepole pine (*Pinus contorta* Dougl.) stand. In their operational use, however, these moisture codes are used as relative indicators of fuel moisture in a wide variety of stands throughout Canada. In interpreting the code values, fire managers understand that for a large region with, for example, an FFMC of 90, the actual moisture in the surface fuels of a pine stand in that region would be different than in the surface fuels of an aspen stand in that same region. They account for the differences due to forest type using their professional experience and with tools such as the FBP System, which allows stand-specific predictions of expected fire behaviour. Several studies (Lawson and Dalrymple 1996; Lawson *et al*. 1997; Wilmore 2001) have developed calibrations of the DMC and DC for specific forest types in western Canada that differed significantly from the FWI System standard; however, no such relationships between FFMC

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and litter moisture content for a range of stand types in Canada are commonly available.

The FWI System has been adopted for use in fire management by a growing list of countries around the world (e.g. New Zealand, Indonesia, Malaysia, Mexico, Portugal and numerous other countries in southern Europe). When adapting the FWI System fuel moisture codes, such as the FFMC, output values are sometimes calibrated to indicate fire potential in the dominant fuel type of the area when that forest fuel type is significantly different from the standard FWI System closed-canopy pine stand. For instance, recently the FFMC was calibrated to better track moisture content in open grass fuels specific to south-east Asia (de Groot *et al*. 2005).

Objective

The present paper describes the development of explicit relationships between observed litter moisture and the FFMC for several major forest types across Canada. The influence of stand density and seasonality on this relationship is also examined, and models are developed to predict actual litter moisture from diurnally adjusted FFMC values in specific stands at specific times of the year. In the FWI System, the fuel moisture models of the different fuel layers of the forest floor are not linked together. However, in reality some moisture exchange between these layers would be expected; for example, one would expect that a wet organic layer would influence moisture in the surface litter. In the present paper, we also investigate this relationship and develop a method to adjust FFMC according to the moisture content in the upper organic layer (as represented by the DMC).

Methods

Data

Fuel moisture data for the current study were obtained from a Canadian Forest Service database assembled as part of an extensive program of fuel moisture and fuel ignitability testing carried out at research sites across Canada from 1939 to 1961 (Paul 1969; Simard 1970)[1]. This field-based research program, which began in the early 1930s at the Petawawa Experimental Research Station (Chalk River, Ontario) and expanded across the country through the late 1930s to 1961, led to the development of the early fire hazard rating systems in Canada, which eventually (in the early 1970s) became the FWI System that is still used today across the country. The program involved daily sampling of moisture content of a variety of fuels (litter, duff, mosses, lichen and heavier woody material) and evaluating the sustainability of flaming with *in situ* small-scale test fires lit with matches or sometimes small 'campfires'.

In the current analysis, data for fuel moisture and fire weather were used from research sites in the provinces of Manitoba (Whiteshell), Saskatchewan (Bittern Creek), Alberta (Kananaskis and Whitecourt), British Columbia (100-Mile House) and the Northwest Territories (Fort Smith). Stand types included in this analysis were: pine (jack pine or lodgepole pine), aspen (generally *Populous tremuloides* Michx.), spruce (black spruce (*Picea marianna* (Mill) B.S.P.) and Engelman spruce (*Picea englemannii*), Douglas fir (*Pseudotsuga menziesii* (Mirbo) Franco) and mixedwood (a mix of deciduous, generally aspen and white birch (*Betula papyrifera* March.) and spruce or pine). In general, the moisture observations reported represent one sample of litter from the forest floor; thus, there can be expected to be a great deal of variability associated with each of these observations. Moisture contents calculated from this sampling, and referred to throughout the present paper, are gravimetric moisture contents (sample moisture content percentage by dry weight).

The original field records contained a rating of canopy closure at every test fire location within a stand. These ratings were summarised and used along with photos and descriptions of the stands to estimate a qualitative rating of stand density (light, moderate, dense) for each stand location. Season (spring, summer, or fall) was determined from records of overstorey green-up and leaf fall at each research site with the exception of the Whitecourt site where these data were unavailable. At the Whitecourt site, all samples taken after 31 May were assigned to the summer category and samples from before that date assigned to the spring category[2].

Daily fire weather data collected at each research station was used to calculate the components of the FWI System following the methods of Van Wagner (1987). Although litter moisture sampling mainly took place in the mid-afternoon, samples were sometimes collected during the morning or evening hours. The Canadian Fire Danger Rating System (CFFDRS) provides a method for adjusting the daily FFMC value to compensate for its diurnal variation (Van Wagner 1972; Lawson *et al*. 1996). The daily FFMC value from the FWI System represents litter moisture content at peak burning conditions on any day, 1600 Local Standard Time (LST). This method of diurnal adjustment was used to estimate an FFMC value at the time each litter sample was collected. Modelled moisture content was calculated from the diurnally adjusted FFMC using the standard FWI System conversion between FFMC and moisture content (mc) (Eqn 1):

$$\text{mc(FFMC)} = 147.27\frac{101 - \text{FFMC}}{59.5 + \text{FFMC}} \qquad (1)$$

Analysis

Sampled moisture content, mc(obs), and modelled moisture content, mc(FFMC), were first plotted to examine their distribution. The points were found to be clustered mainly at the dry end of the moisture scale, and data were also observed to have increasing variability with increasing moisture content. This latter observation is quite common in studies of fuel moisture in both litter and organic fuels. From this visualisation of the data, it seemed clear the moisture content data needed to be transformed to a more normal distribution for proper interpretation of the statistical analysis. Both mc(obs) and mc(FFMC) were transformed using

[1] A more detailed report describing the test fire procedures and experimental sites is being prepared: J. L. Beverly and B. M. Wotton: The Canadian small-scale test database: historical overview and data documentation. Canadian Forest Service Northern Forestry Centre, Information Report.

[2] Data (unpublished) from fire tower observations (1999–2004) of leaf flush indicate that leaf flush in aspen occurs very close to the end of May in this area on average. Although this is of course an approximation, we do not feel it has influenced the results greatly.

the natural logarithm to normalise the variance with increasing dryness.

Observed moisture data spanned a range from close to 0% to over 400%; however, the majority of the observations tended towards the dry end of the scale. This is to be expected as moisture sampling was in all likelihood not carried out frequently on very wet days when researchers knew there would be no chance of having a successful test fire ignition. Fire managers are of course most interested in fuel moisture at the dry end of the scale where it might affect the ignition potential or rate of spread of a fire. To ensure our models were most accurate at this dry end (and not influenced by a smaller number of points with undue leverage at the high end of the moisture range), we excluded the highest moisture content data by removing records where daily FFMC was less than 75 (equivalent to a moisture content of 28.5% in the standard FWI System conversion, Eqn 1). We chose this value because, in general, in operational use, fire managers consider it necessary to have an FFMC of higher than 75 for potential fire spread. Models developed using the full dataset were quite similar to the models developed using this reduced dataset, though the former tended to over-predict litter moisture content at the dry end (<10%).

The dataset used in the present study was made up of a series of samples taken daily from several different locations. Sampling was carried out at each of these locations over several years, under differing weather systems throughout each year and from year to year. In addition, we only considered the period when sampling was physically carried out at the research station and, within that subset, only days where FFMC > 75. Thus, the data stream within each year at an individual location was disjointed, made up of short sequences of day-to-day observations. Although the structure of the dataset suggested a repeated analysis methodology might be used with stand locations defined as ‘subject’, no truly appropriate common and repeated treatment effect could be identified. Given these considerations, we decided to carry out a basic multivariate linear regression to explore the influence of the various stand and seasonal predictors on the relationship between observed and estimated moisture content, and the influence of other factors. In interpreting the strength of the final model developed here, it should be recognised that we have not compensated for this structure in the dataset, and it is possible that some stands have received higher or lower weighting because of this, which may have influenced the explained variability.

We first explored significance of the relationship between mc(obs) and mc(FFMC) for all data points of the reduced dataset (where FFMC > 75) using analysis of variance. We then tested the influence of each of three categorical variables individually on the relationship between mc(obs) and mc(FFMC). Forest type was coded into a five-level categorical variable (FOREST = pine, spruce, Douglas fir, mixed, or deciduous) and its influence examined. The influence of stand density was tested through the inclusion of a three-level categorical variable describing stand density (DENSITY = Light, Moderate, or Dense). The effect of time of year was then tested by adding a three-level categorical variable for season (SEASON = Spring, Summer, or Fall). Dummy variable structures used in the statistical analysis involving these three categorical variables are shown in Table 1. Interaction terms between forest type and estimated moisture, FOREST × ln(mc(FFMC)), and stand density and estimated moisture, DENSITY × ln(mc(FFMC)), and between season and estimated moisture, SEASON × ln(mc(FFMC)), were also added to the analysis of these individual effects models. After this exploration of the individual effects from each of the three main variables, we tested co-linearity in the four main predictors of the final model form. There were no indications that there was strong co-linearity in any of the main terms in the final model reported here. We then developed a full model by using a technique very similar to forward stepwise selection. That is, we added the term that had the highest influence on the relationship between mc(obs) and mc(FFMC) to the model, then the next term, etc. Interaction terms were then added in a similar fashion.

Table 1. Dummy variable matrix definition for categorical variables used in analysis of variance

Variable	Category	Dummy variable matrix row
FOREST	Deciduous	1 0 0 0
	Douglas fir	0 1 0 0
	Mixedwood	0 0 1 0
	Pine	0 0 0 1
	Spruce	0 0 0 0
SEASON	Fall	1 0
	Summer	0 1
	Spring	0 0
DENSITY	Dense	1 0
	Light	0 1
	Moderate	0 0

The form of the linear model from these analyses is shown in Eqn 2:

$$\begin{aligned}\ln(\text{mc(obs)}) = \beta_0 &+ \beta_1 \cdot \ln(\text{mc(FFMC)}) + \beta_2 \cdot \text{FOREST} \\ &+ \beta_3 \cdot \text{DENSITY} + \beta_4 \cdot \text{SEASON} \\ &+ \beta_5 \cdot \text{FOREST} \times \ln(\text{mc(FFMC)}) \\ &+ \beta_6 \cdot \text{DENSITY} \times \ln(\text{mc(FFMC)}) \\ &+ \beta_7 \cdot \text{SEASON} \times \ln(\text{mc(FFMC)}) \qquad (2)\end{aligned}$$

Although only this model form is shown, as described above, each variable (and subsequently its interaction with mc(FFMC)) was tested individually for its influence on the relationship between mc(obs) and mc(FFMC). These model forms and results will not be shown in the present paper as they can be generalised with the final model form shown in Eqn 2. This individual testing was carried out to ensure a proper understanding of the influence of each variable with and without the influences of the other variables.

The influence of moisture content in the duff layer on the general relationship between observed litter moisture and that predicted from the FFMC was tested in an ANOVA using the simple model given in Eqn 3:

$$\ln(\text{mc(obs)}) = \beta_0 + \beta_1 \cdot \ln(\text{mc(FFMC)}) + \beta_2 \cdot \text{mc(DMC)} \qquad (3)$$

In Eqn 3, mc(DMC) is the moisture content equivalent of the DMC and is calculated using the standard relation for this moisture code from the FWI System given in Eqn 4:

$$\text{mc(DMC)} = 20 + e^{-\left(\frac{\text{DMC}-244.72}{43.43}\right)} \qquad (4)$$

A plot of ln(mc(obs)) *v*. mc(DMC) revealed no significant change in variability throughout the range of mc(DMC), and thus this term was left untransformed. In addition to the ANOVA analysis, we examined the correlation between FFMC and DMC in the dataset and found it to be 0.29, which we felt was acceptable in terms of its strength for these terms in this linear regression.

This analysis showed that mc(DMC) did have a strong influence on the relationship between mc(obs) and mc(FFMC), and therefore, the mc(DMC) term was added to the larger model with forest type, season and stand density. The full form of the model tested was then:

$$\begin{aligned}\ln(\mathrm{mc(obs)}) = \beta_0 &+ \beta_1 \cdot \ln(\mathrm{mc(FFMC)}) + \beta_2 \cdot \mathrm{FOREST} \\ &+ \beta_3 \cdot \mathrm{DENSITY} + \beta_4 \cdot \mathrm{SEASON} \\ &+ \beta_5 \cdot \mathrm{FOREST} \times \ln(\mathrm{mc(FFMC)}) \\ &+ \beta_6 \cdot \mathrm{DENSITY} \times \ln(\mathrm{mc(FFMC)}) \\ &+ \beta_7 \cdot \mathrm{SEASON} \times \ln(\mathrm{mc(FFMC)}) \\ &+ \beta_8 \cdot \mathrm{mc(DMC)}. \qquad (5)\end{aligned}$$

Results and discussion

After removing records where daily FFMC < 75, there were a total of 6853 paired observations of mc(obs) and mc(FFMC) in the selected stand types in the dataset. Table 2 shows a simple summary of observed moisture contents, and FFMC and DMC values in the dataset. Table 3 summarises these numbers in terms of the breakdown by each of forest type, season and density. This table shows that the bulk of the observations occurred during the summer months and in pine stands.

The log-transformed plot of mc(obs) and mc(FFMC) in Fig. 1 shows that there is a strong general relationship between observed moisture content and moisture content as estimated by the FFMC model. Fig. 1 also reveals that there is considerable variability in this relationship. The analysis of variance of this simple relationship gives an $R^2 = 35\%$ and an F-value = 3625.0 ($P < 0.0001$).

Analysis of variance was used to examine the influence of organic layer moisture on the overall relationship between observed and modelled moisture using the model given in Eqn 3. This analysis showed that moisture in the upper portions of the organic layer (as modelled by the DMC) did have a significant influence on the relationship between mc(obs) and mc(FFMC). This relationship had an $R^2 = 38\%$ (model $F = 2065$, $P < 0.0001$). A summary of the regression coefficients is presented in Table 4. The sign of the coefficient

Table 3. Frequencies for litter moisture observations in each of the categories of the main variables tested in the analysis of variance

FOREST	Frequency	SEASON	Frequency	DENSITY	Frequency
Deciduous	1837	Spring	737	Light	436
Fir	260	Summer	5464	Moderate	5319
Mixedwood	1104	Fall	652	Dense	1098
Pine	3300				
Spruce	352				

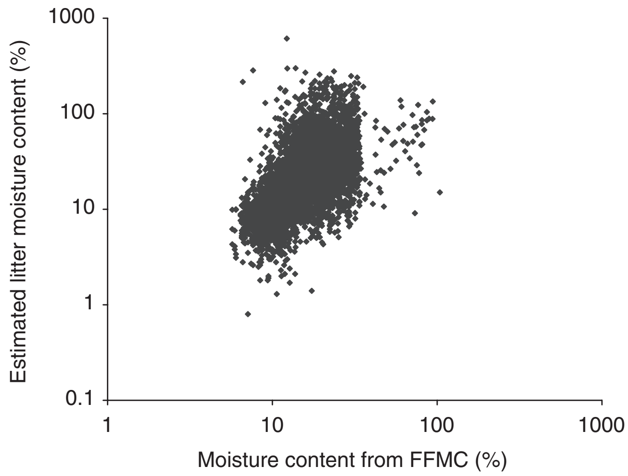

Fig. 1. Log-transformed plot of observed moisture *v*. modelled moisture from diurnally adjusted Fine Fuel Moisture Code (FFMC). Values here are shown on log-transformed axes to eliminate increasing variability with moisture content (MC). Data shown are those points on days where the daily FFMC ≥ 75.

Table 4. Coefficients from the ANOVA examining the effect of duff moisture on the observed and modelled moisture content relationship (model form is given in Eqn 3)

Model (Variable)	Coefficient	Standard error	Student-*t* value	*P*
Intercept (β_0)	0.186	0.026	7.39	<0.0001
ln(mc(FFMC)) (β_1)	0.794	0.011	73.72	<0.0001
mc(DMC) (β_2)	0.0032	0.0001	30.39	<0.0001

Table 2. Summary of observed and calculated moisture content for all data in the experiment ($n = 6853$)

FFMC, diurnally adjusted Fine Fuel Moisture Code; DMC, Duff Moisture Code; mc, percentage moisture content (gravimetric)

	Mean	Median	Standard deviation	Range			
				Min.	5th percentile	95th percentile	Max.
mc(obs) (%)	25.8	16.4	28.6	0.8	6.6	78.0	613
FFMC	85.5	86.9	5.7	34.6	74.5	92.1	95
mc(FFMC) (%)	16.0	14.2	7.1	5.7	8.6	29.1	104
DMC	36	28	28	3.1	9	97	238
mc(DMC) (%)	161	168	59	21.1	50	248	281

Table 5. Analysis of variance summary for the full model of litter moisture given in Eqn 5
FFMC, diurnally adjusted Fine Fuel Moisture Code; DMC, Duff Moisture Code; mc, percentage moisture content (gravimetric)

Variable	d.f.	Cumulative model[A] R^2	Final model		
			Type III sums of squares	*F*-value	*P*
ln(mc(FFMC))	1	34.6	135.7	467.3	<0.0001
mc(DMC)	1	37.6	92.6	318.9	<0.0001
SEASON	2	40.4	4.38	7.54	0.0005
FOREST	4	47.5	3.03	2.61	0.0335
DENSITY	2	48.7	5.01	8.63	0.0002
DENSITY × ln(mc(FFMC))	2	49.0	9.60	16.5	<0.0001
SEASON × ln(mc(FFMC))	2	49.4	10.6	18.2	<0.0001
FOREST × ln(mc(FFMC))	4	49.6	4.96	4.27	0.0019

[A]This represents the R^2 value of the full model after the addition of each variable listed (that is, the R^2 value of each of the nested models created in development of the full model in Eqn 5).

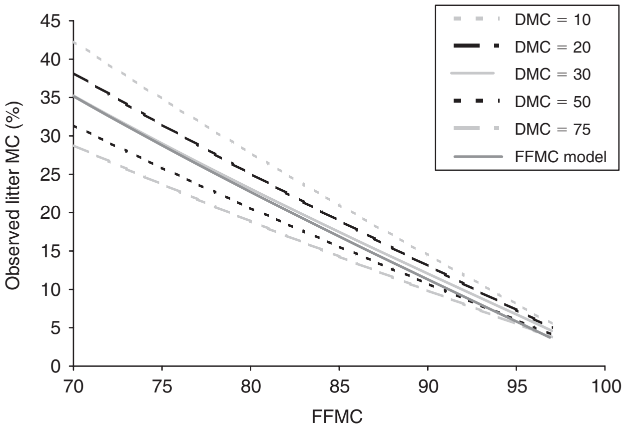

Fig. 2. The impact of changing Duff Moisture Code (DMC) on the observed litter moisture content (MC) and Fine Fuel Moisture Code (FFMC) relationship. This example is a moderate-density pine forest in the summer.

Table 6. Coefficient values for full model based on Eqn 5
FFMC, diurnally adjusted Fine Fuel Moisture Code; DMC, Duff Moisture Code

Variable (coefficient in Eqn 5)	Category	Coefficient	s.e.
Intercept (β_0)	–	0.4478	0.2913
ln(mc(FFMC)) (β_1)	–	0.6297	0.1063
	Deciduous	−0.0092	0.2804
	Fir	−0.7189	0.3636
FOREST (β_2)	Mixed	−0.0586	0.2783
	Pine	0.1126	0.2644
	Spruce	0.0	–
	Deciduous	0.0936	0.1002
	Fir	0.1979	0.1369
FOREST × ln(mc(FFMC)) (β_5)	Mixed	0.0757	0.0991
	Pine	−0.0576	0.0941
	Spruce	0.0	–
	Spring	0.0	–
SEASON (β_4)	Summer	−0.5951	0.1534
	Fall	−0.5698	0.2532
	Spring	0.0	–
SEASON × ln(mc(FFMC)) (β_7)	Summer	0.3470	0.0593
	Fall	0.4274	0.0942
	Light	0.2912	0.2144
DENSITY (β_3)	Moderate	0.0	–
	Dense	0.3329	0.0643
	Light	−0.1912	0.0802
DENSITY × ln(mc(FFMC)) (β_6)	Moderate	0.0	–
	Dense	0.1208	0.0060
mc(DMC) (β_8)	–	0.00223	0.00012

indicates that, for a constant value of FFMC, a wetter upper organic layer leads to wetter litter on the surface. Plots of this relationship based on the full model results (from Table 5, Table 6 and Eqn 5) for a moderate density pine forest type in the summer are shown for several DMC values in Fig. 2.

The analysis of the individual influence of each term on the relationship between mc(obs) and mc(FFMC) showed each of FOREST, SEASON and DENSITY were statistically significant. Interaction terms for each variable with mc(FFMC) were also significant, indicating the slope of relationship between ln(mc(FFMC)) and ln(mc(obs)) varied with each factor as well as the intercept. A summary of the full model result appears later in Tables 5 and 6.

That FOREST had a significant influence on the relationship between observed *v.* modelled litter moisture content is not surprising. The dominant species in a stand will influence the type of litter material on the forest floor (e.g. long needle, short needle, leaf). Furthermore, differing canopy structure among forest types can lead to variation in solar radiation, rainfall and wind penetration into a stand, all influences that would influence surface microclimate and the moisture of material on the forest floor.

The sign of the coefficient on the DENSITY term implied that as stands of the same forest type become denser, observed litter moisture increases for a given FFMC. That is, given a constant value of FFMC from a nearby weather station, a forest stand with a denser canopy would have a wetter litter layer than would a lower density stand. This is most likely a function of the decrease

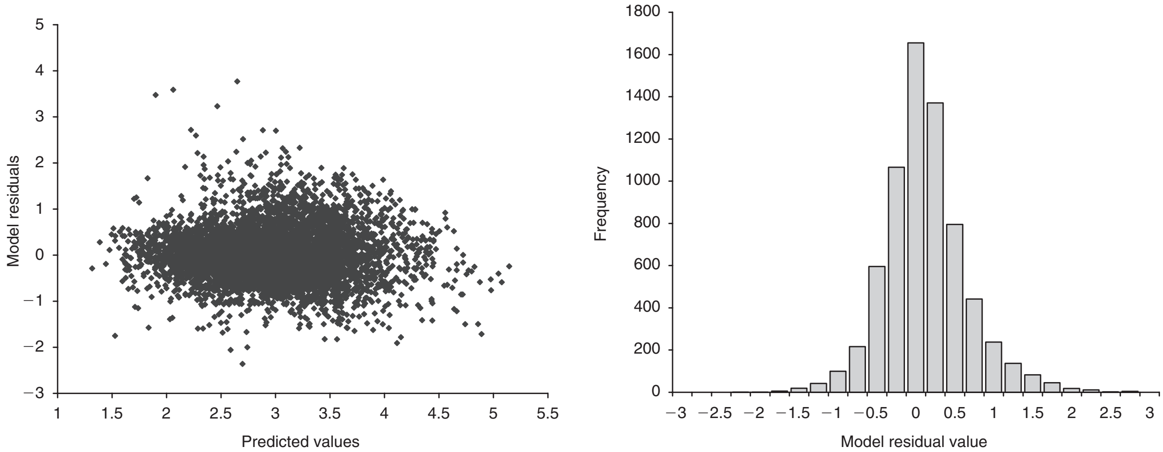

Fig. 3. Residuals from the model fit to Eqn 5: (*a*) residual values *v*. fitted values; and (*b*) a frequency chart of residual distribution.

in solar radiation incident on fuels, and perhaps a reduced wind flow over the surface of the forest floor as stand density increases.

The influence of SEASON in the deciduous and mixedwood types was not surprising as leaf flush and leaf fall would modify the surface microclimate in these stands. The sign of the coefficients (Table 6) of each SEASON category indicated that, given a day in both seasons with the same FFMC value, litter would be drier in the spring than in the summer or fall. This seasonal difference does have an observed effect on fire behaviour, particularly in mixedwood and deciduous stands. Currently the FBP System modifies expected fire behaviour in mixedwood stands corresponding to a change brought on by canopy leaf flush in summer. Given the same FFMC value and wind speed, fire behaviour potential in mixedwood stands in summer is reduced over that expected in the spring.

That SEASON influenced the relationship between mc(obs) and mc(FFMC) for all the forest types was unexpected, given that there is no major change in the canopy of conifer forest types studied with the changing season. We examined the strength of the seasonal effect for the pine stand alone as we had the largest subset of data for this type (model: $\ln(\text{mc(obs)}) = \beta_0 + \beta_1 \cdot \ln(\text{mc(FFMC)}) + \beta_2 \cdot \text{SEASON}$) and found a significant seasonal signal existed (SEASON: d.f. = 2, $F = 72.4$, $P < 0.0001$). This sign of β_2 meant that, given the same value of FFMC, pine litter in the spring was drier than in the summer. We initially hypothesised that the seasonality effect in pine stands might be due to the influences of moisture content of the organic layer that are not accounted for by the FFMC; the problem with this hypothesis, however, is that the duff layer is generally wetter in spring than summer, and a wetter duff layer would have the opposite effect to that observed. Analysis of the significance of SEASON in the pine forest type with a duff moisture content term included showed that SEASON indeed remained a significant factor in the relationship between mc(obs) and mc(FFMC) after adjusting for the influence of organic moisture (SEASON: d.f. = 2, $F = 61.5$, $P < 0.0001$; mc(DMC): d.f. = 1, $F = 129.5$, $P < 0.0001$). Thus, the differences in litter moisture from spring to summer for similar FFMC values are due to something other than the seasonal variation in duff moisture.

Table 5 presents the basic ANOVA summaries of the significance of each variable, and Table 6 lists the model coefficients for the full model form given in Eqn 5. The final model has an R^2 of 50% and a model F-value = 373.7 (d.f. = 18, $P < 0.0001$). It is important to note that the litter moisture observations from the small-scale test fire database are a moisture estimate based on, generally, one sample taken from the forest floor. Thus these individual estimates have a sizeable standard error associated with them, and this no doubt contributes somewhat to the unexplained variability in these results. No discernable structure could be found in the examination of the residuals of the model based on Eqn 5. Fig. 3*a* shows a plot of predicted values *v*. residuals from this relationship, and Fig. 3*b* shows a fairly normal distribution of residual values.

Using the coefficients in Table 6, specific equations to estimate actual litter moisture content from FFMC can be developed for each forest type, stand density, or season, and adjustments to litter moisture can be made to account for the moisture content of the duff. For example, for a pine forest with moderate closure in summer, the resultant model for moisture content (mc) would be,

$$\text{mc} = e^{-0.0346+0.9091\times\ln(\text{mc(FFMC)})+0.002232\times\text{mc(DMC)}}$$

whereas the same pine forest, with light canopy closure, in summer gives the following model,

$$\text{mc} = e^{0.2566+0.7179\times\ln(\text{mc(FFMC)})+0.002232\times\text{mc(DMC)}}$$

For a deciduous forest with moderate canopy closure in the summer, surface litter moisture can be predicted with the model,

$$\text{mc} = e^{-0.1564+1.0603\times\ln(\text{mc(FFMC)})+0.002232\times\text{mc(DMC)}}$$

The relationships between actual litter moisture and FFMC in these examples are shown in the plots in Fig. 4. A list of equations for each of forest type, stand density and season category can be found in Table A1 in Appendix 1. Correlations of predicted *v*. observed moisture for each data subset are also included in this table. This highlights where the model works well and where it does not, but more importantly gives potential users of the model an idea of which subsets (based on the forest type, stand density

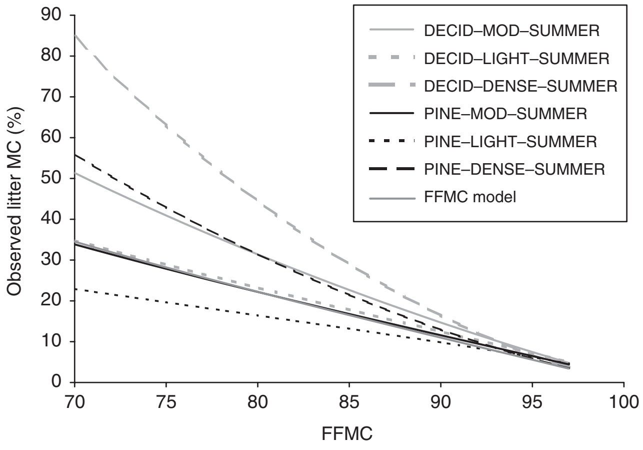

Fig. 4. A comparison of the impact of stand density on litter moisture content and Fine Fuel Moisture Code (FFMC) relationship for the pine and deciduous forest type. The summer class and a Duff Moisture Content value of 36 have been used for all models.

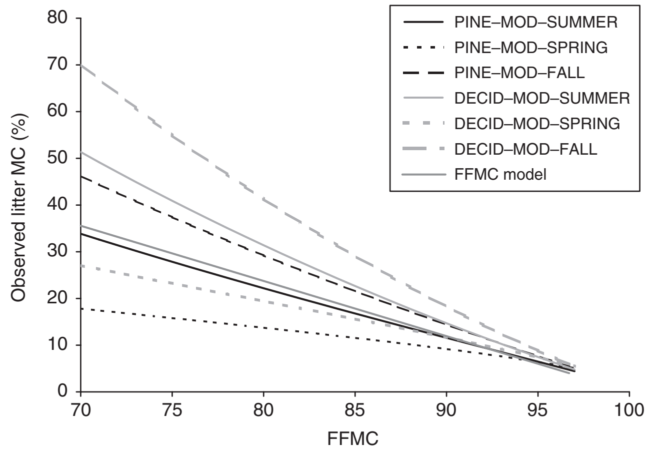

Fig. 5. A comparison of the impact of season on the litter moisture and Fine Fuel Moisture Code (FFMC) relationship for the pine and deciduous forest type. A moderate stand density and a Duff Moisture Content value of 36 have been used for all models.

and season classifications) of our historical database contained no data. The model form (Eqn 5) allows development of models for these missing categories using the relationships defined by the entire dataset, and these models have been included in Appendix 1 for completeness; however, for these subsets with little or no data, caution should be used in interpreting the model predictions.

Fig. 4 compares the relationship between FFMC and observed surface litter moisture for pine and deciduous forest types for different stand densities. These relationships are for the summer period and for a DMC value of 36 (142% mc), which is the average DMC in the dataset used to derive these equations. As one would suspect, litter in the deciduous stands is wetter than in the pine stands for each density category for any given value of FFMC. As surface fuels become very dry, differences between stand types (between deciduous and pine) and across stand densities tend to disappear.

Fig. 5 shows a similar comparison to that in Fig. 4, but with stand density held constant at Moderate and with season varying. Here again for each season, litter in the deciduous forests is wetter than that in pine forests for any given level of FFMC, until very dry conditions are reached. The difference season makes on the relationship between FFMC and actual litter moisture in the pine forest can be seen in this plot.

Fig. 6 contrasts litter moisture in the mixedwood forest type with spruce stands, holding stand density constant at Moderate. In the FBP System, the mixedwood type is considered a mix of spruce and deciduous overstorey. This comparison shows that, within each season, litter on the surface of the mixedwood forest is wetter than litter in the spruce forest at a given value of FFMC. This result agrees with the way the FBP System predicts fire spread rate to change between these forest types from spring to summer.

Also of note in Figs 4, 5 and 6 is the similarity of the pine curves to the standard FWI System curve for the FFMC and moisture content relationship given by Eqn 1. The summer models of moderate-density pine closely track the standard relationship. This agreement is not surprising as the FFMC model is generally assumed to represent a moderate-closure pine stand. The moderate-density spruce stand summertime model is also very close to the standard relationship of Eqn 1.

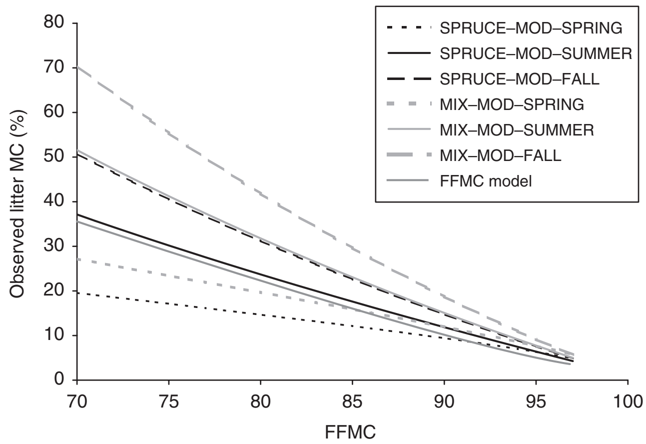

Fig. 6. A comparison of the effect of season on the litter moisture and Fine Fuel Moisture Code (FFMC) relationship for the mixedwood and pure spruce forest types. A moderate stand density and a Duff Moisture Content value of 36 have been used for all models.

A validation dataset

The model from Eqn 5 was tested against a small dataset collected during the summer of 2004 at a site ~8 km west of Sault Ste Marie, Ontario. This area included several different forest stand types in close proximity (all within less than 1 km of one another). Five distinctly different stands were chosen for litter moisture sampling at this location: a low density jack pine stand, a mixedwood stand of moderate density, an aspen stand of moderate density, a young jack pine plantation of moderate density, and a red pine (*Pinus resinosa* Ait.) stand with full crown closure.

Sampling took place on 29 days throughout the summer, beginning on 8 May, and ending on 23 August. Litter moisture

Table 7. Moisture and weather summary over the days of sampling during 2004 at the Sault Ste Marie site

RH, Relative Humidity; FFMC, diurnally adjusted Fine Fuel Moisture Code; DMC, Duff Moisture Code

	Litter moisture[A] (%)	Temperature (°C)	RH (%)	Rainfall (mm)	FFMC	DMC
n	165	29	29	29	29	29
Mean	40.2	19.6	57	3.12	73.6	15
Median	25.8	20.4	55	0	84.3	13
Minimum	11.5	9.3	28	0	17.3	2
Maximum	209.0	27.0	98	34.5	89.6	35

[A]This value is calculated from daily average litter moisture content for each stand.

Table 8. Correlation coefficients from comparison of observed litter moisture across all stands and stand-specific moisture content estimated using Eqn 5

In all cases $n = 165$ and all correlations are significant with $P < 0.0001$. FFMC, diurnally adjusted Fine Fuel Moisture Code

	Diurnally adjusted FFMC		Hourly FFMC		Daily FFMC	
	Raw	Stand-adjusted	Raw	Stand-adjusted	Raw	Stand-adjusted
Correlation coefficient	0.67	0.84	0.63	0.79	0.68	0.83

in each of the stands was sampled generally during the mid-afternoon over a period of less than 2 hours. The litter moisture estimate for each stand on each day represents the average of four to six separate samples of litter. On average, litter samples were ~10 g (dry weight).

We have classified the stands sampled at the Sault Ste Marie site into the categories defined earlier in the present paper: the lower density jack pine stand was classified as pine–light density; the jack pine plantation and red pine plantation were classified as pine–moderate density; the aspen stand was classified as deciduous–moderate density; and the mixedwood stand was classified as mixedwood–moderate density. The date of leaf flush at the site was observed to be 20 May. All samples taken before this date were considered spring samples and all others summer samples.

The summer of 2004 in the Sault Ste Marie area was somewhat cooler and wetter than usual, and unfortunately very low moisture conditions (litter moisture < 10%) were not observed in any of the stands over the summer. Table 7 summarises the daily fire weather observed at the on-site weather station (at 1300 LDT each day) on the days when sampling took place.

Daily FFMC was calculated from the on-site weather records (from the methods in Van Wagner 1987), and this was used to calculate the diurnally adjusted FFMC for the time of each sample using the Lawson *et al.* (1996) procedure. In addition, hourly weather observations from the weather station were used to calculate hourly FFMC (HFFMC) (Van Wagner 1977) corresponding to the hour each sample was taken.

Each of the three calculated values (FFMC, diurnally adjusted FFMC and HFFMC) were converted to an estimated litter moisture content for each of the different stands that were sampled using Eqn 5, and also by using the standard relationship given in Eqn 1 (these latter will be referred to as 'raw' calculated values). Plots of calculated *v.* observed moisture were examined, and the Pearson correlation coefficient between observed moisture content and calculated moisture content were determined for the entire dataset. These results in Table 8 show that stand-adjusted moisture content estimates (Eqn 5) from each of daily FFMC, HFFMC and diurnally adjusted FFMC were more strongly correlated with the observed moisture content than the raw moisture content values calculated using the standard formula (Eqn 1).

The correlation between predicted and observed moisture was examined for each stand type using the stand-specific adjustment of the FFMC. These results appear in Table 9, and show that the improvement in correlation is strongest for the deciduous and mixedwood types. The jack pine forest type shows little difference in correlation between the raw (unadjusted FFMC) and the stand-adjusted model results. This is because there is little difference between the standard formula and Eqn 5 for these stands (see the line plotted for Pine–Moderate–Summer in Fig. 5). Estimates of litter moisture content in the red pine stand, however, were not improved by the stand type (pine–moderate closure) we chose to represent it in the Eqn 5 model. In fact, the stand-adjusted moisture content had a lower correlation than the diurnally adjusted value. The composition and structure of the red pine litter layer was distinctly different from the jack pine stand, however. This red pine stand studied had a thick layer (~5 cm) of undecayed needle litter that separated the bulk of the litter from the forest floor. Litter in stands of this type tends to be dryer than litter that sits more directly on the wet forest floor. These results suggest that the model developed here (Eqn 5) should not be used for stands where the surface litter is not strongly influenced by the moisture in the forest floor.

Conclusions

The analysis presented has shown that, although FFMC is correlated with actual litter moisture content in a range of Canadian forest types, the relationship between litter moisture and the FWI System's FFMC varies with forest type, stand density and season. In addition, the relationship between FFMC and litter moisture is found to be influenced by the level of moisture in the underlying duff layer, as represented by the FWI System's DMC. Models explicitly describing these relationships were developed and can be used in these types of stands when actual litter moisture estimates are required for specific fire management or fire research applications.

Future research

The results of these analyses represents an initial step in the development of stand-specific moisture models for use in forest fire behaviour prediction in major fuel types in the boreal forests of Canada. On one hand, the analysis has shown what has long been known: that the relationship between the FWI System's FFMC and actual litter moisture content varies by stand type and stand density. The analysis, however, has allowed us some quantitative understanding of that difference over several very

Table 9. Correlation between observed litter moisture and moisture content estimated directly from diurnally adjusted Fine Fuel Moisture Code (labelled as 'raw') and from Eqn 5 (labelled as 'stand-adjusted')
All correlations are significant with $P < 0.0001$

Model chosen		Stand sampled at Sault Ste Marie site				
		Jack pine	Jack pine plantation	Red pine plantation	Aspen	Mixedwood
		Pine Light Spring/Summer	Pine Moderate Spring/Summer	Pine Moderate Spring/Summer	Deciduous Moderate Spring/Summer	Mixed Moderate Spring/Summer
Number of samples		33	31	36	33	32
Correlation coefficient	Raw	0.84	0.82	0.87	0.74	0.79
	Stand-adjusted	0.89	0.83	0.70	0.85	0.86

important stand types in Canada. Further research should focus on defining these differences over a wider range of forest types with well-quantified (and perhaps controlled through thinning) stand densities. In addition to characterising the relationship between the FFMC and actual litter moisture for a range of forest stand types, future work should focus on development of simple yet robust moisture exchange models capable of accounting for the influence of litter type, the influence of canopy type and structure on solar radiation, surface winds and canopy throughfall, and the influence of moisture beneath the surface of the forest floor.

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Appendix 1

Table A1. Models of actual litter moisture content based on Fine Fuel Moisture Code (FFMC), forest type, season, stand density and Duff Moisture Code (DMC)

Values for mc(FFMC) and mc(DMC) are calculated from FFMC and DMC using the FWI System relations given here in Eqn 1 and Eqn 4 respectively. Bold r values are significant at $P < 0.05$

Model variable			Model	*n*	*r*
Forest	Density	Season			
Deciduous	Light	Spring	$mc = EXP\{0.7299 + 0.5221 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	–	–
Douglas fir	Light	Spring	$mc = EXP\{0.0202 + 0.6264 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	36	**0.61**
Mixed	Light	Spring	$mc = EXP\{0.7977 + 0.5042 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	–	–
Pine	Light	Spring	$mc = EXP\{0.8517 + 0.3709 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	24	**0.29**
Spruce	Light	Spring	$mc = EXP\{0.7391 + 0.4285 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	–	–
Deciduous	Moderate	Spring	$mc = EXP\{0.4387 + 0.7133 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	130	**0.24**
Douglas fir	Moderate	Spring	$mc = EXP\{-0.2710 + 0.8176 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	36	**0.72**
Mixed	Moderate	Spring	$mc = EXP\{0.5065 + 0.6954 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	136	**0.57**
Pine	Moderate	Spring	$mc = EXP\{0.5605 + 0.5621 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	279	**0.46**
Spruce	Moderate	Spring	$mc = EXP\{0.4479 + 0.6197 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	18	**0.79**
Deciduous	Dense	Spring	$mc = EXP\{-0.2449 + 1.0462 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	76	**0.67**
Douglas fir	Dense	Spring	$mc = EXP\{-0.9546 + 1.1505 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	–	–
Mixed	Dense	Spring	$mc = EXP\{-0.1771 + 1.0283 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	–	–
Pine	Dense	Spring	$mc = EXP\{-0.1231 + 0.8950 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	–	–
Spruce	Dense	Spring	$mc = EXP\{-0.2357 + 0.9526 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	–	–
Deciduous	Light	Summer	$mc = EXP\{0.1348 + 0.8691 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	–	–
Douglas fir	Light	Summer	$mc = EXP\{-0.5749 + 0.9734 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	83	**0.51**
Mixed	Light	Summer	$mc = EXP\{0.2026 + 0.8512 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	–	–
Pine	Light	Summer	$mc = EXP\{0.2566 + 0.7179 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	241	**0.61**
Spruce	Light	Summer	$mc = EXP\{0.1440 + 0.7755 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	–	–
Deciduous	Moderate	Summer	$mc = EXP\{-0.1564 + 1.0603 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	652	**0.57**
Douglas fir	Moderate	Summer	$mc = EXP\{-0.8661 + 1.1646 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	88	**0.60**
Mixed	Moderate	Summer	$mc = EXP\{-0.0886 + 1.0424 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	905	**0.67**
Pine	Moderate	Summer	$mc = EXP\{-0.0346 + 0.9091 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	2314	**0.64**
Spruce	Moderate	Summer	$mc = EXP\{-0.1472 + 0.9667 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	313	**0.57**
Deciduous	Dense	Summer	$mc = EXP\{-0.8400 + 1.3932 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	771	**0.69**
Douglas fir	Dense	Summer	$mc = EXP\{-1.5497 + 1.4975 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	–	–
Mixed	Dense	Summer	$mc = EXP\{-0.7722 + 1.3753 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	–	–
Pine	Dense	Summer	$mc = EXP\{-0.7182 + 1.2420 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	97	**0.59**
Spruce	Dense	Summer	$mc = EXP\{-0.8308 + 1.2996 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	–	–
Deciduous	Light	Fall	$mc = EXP\{0.1601 + 0.9495 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	–	–
Douglas fir	Light	Fall	$mc = EXP\{-0.5500 + 1.0538 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	11	0.09
Mixed	Light	Fall	$mc = EXP\{0.2279 + 0.9316 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	–	–
Pine	Light	Fall	$mc = EXP\{0.2819 + 0.7983 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	41	**0.81**
Spruce	Light	Fall	$mc = EXP\{0.1693 + 0.8559 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	–	–
Deciduous	Moderate	Fall	$mc = EXP\{-0.1311 + 1.1407 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	70	**0.59**
Douglas fir	Moderate	Fall	$mc = EXP\{-0.8408 + 1.2450 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	6	**0.86**
Mixed	Moderate	Fall	$mc = EXP\{-0.0633 + 1.1228 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	63	**0.70**
Pine	Moderate	Fall	$mc = EXP\{-0.0093 + 0.9895 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	288	**0.57**
Spruce	Moderate	Fall	$mc = EXP\{-0.1219 + 1.0471 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	21	0.33
Deciduous	Dense	Fall	$mc = EXP\{-0.8147 + 1.4736 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	138	**0.78**
Douglas fir	Dense	Fall	$mc = EXP\{-1.5244 + 1.5779 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	–	–
Mixed	Dense	Fall	$mc = EXP\{-0.7469 + 1.4557 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	–	–
Pine	Dense	Fall	$mc = EXP\{-0.6929 + 1.3224 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	14	**0.65**
Spruce	Dense	Fall	$mc = EXP\{-0.8055 + 1.3800 \times \ln(mc(FFMC)) + 0.002232 \times mc(DMC)\}$	–	–