3A.2 A GRASS MOISTURE MODEL FOR THE CANADIAN FOREST FIRE DANGER RATING SYSTEM

B. Mike Wotton
Canadian Forest Service, Natural Resources Canada

1. INTRODUCTION

Grass fires are a common occurrence in rural and forested areas in Canada, particularly in the spring. In the spring, once snow-free, matted grass from the previous summer dries quickly and can easily support combustion. This dryness coupled with the exposed nature of these fuels, and the consequent exposure to winds, means that these fires can spread fast and easily escape control.

In Canada fire behaviour in grass is modeled by the O-1 model in the Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992). Rate of spread (ROS) prediction models were developed by developing empirical relationships between observed rate of spread in grassland experimental burning (carried out in Australia) and the Initial Spread Index (ISI) component of the Canadian Fire Weather Index (FWI) System (Van Wagner 1987). The ISI is a non-linear combination of an exponential wind speed function and a function of moisture content based on the Fine Fuel Moisture Code (FFMC) of the FWI System. This FFMC has at its core a fast reacting moisture exchange model that tracks moisture in forest litter: fine dead needles and twigs on the surface of the forest floor. It is calculated and used across Canada on a daily basis and has been found to be very well-correlated with litter moisture content across a wide variety of fuels in Canada (Wotton and Beverly 2007); it has also been found to be a good indicator of fire ignition and spread potential. A daily value of FFMC is calculated using 1200 LST observations of screen level temperature and humidity, a 10 m open wind speed and 24 hours of accumulated rainfall. Fire weather observations are taken in a standardized large exposed clearing, to local terrain influences on observations.

The FFMC was developed to model litter moisture in a closed canopy conifer stand and as such implicitly compensates for the sheltering effect of the canopy from rain and solar radiation and the reduction in surface wind caused by the forest stand. Moisture exchange in this surface litter layer in this boreal forest environment is also influenced by the wetness of the organic layer below it (Wotton and Beverly 2007). As such the FFMC has a slower reaction time than one might expect were the litter layer more exposed without a thick moist organic layer.

* *Corresponding author current address*: Mike Wotton, Canadian Forest Service- Natural Resources Canada, Faculty of Forestry-University of Toronto, 33 Willcocks St. Toronto, Ontario, Canada, M5S 3B3; e-mail mike.wotton@utoronto.ca

Grass fuel types, on the other hand, can occur as exposed (unshaded) fields and moisture content of the litter layer is not generally influenced by moisture in an organic layer or the soil underneath. Therefore it is reasonable to assume that grass fuels would be much faster drying than forest litter. This is in fact a common observation; grass fuels have been observed to dry quickly and can be ready to sustain fire spread just a few hours after rain (e.g., Cheney and Sullivan 2008).

In this paper a new moisture model for exposed fully cured grass fuels is developed. This new model is based on the general structure of the FWI System's FFMC however it includes explicit adjustment for the exposure of the fuel layer to solar radiation and a response time appropriate for fine grass fuels. The goal of this work was to create a model that could be used by fire managers in Canada using the data they currently have access to plus solar radiation. Observations of diurnal and day-today variation in grass moisture from the field were used as a validation dataset for the model.

2. METHODS

2.1 Model development

The new moisture model developed here relied upon the structure of the hourly FFMC, a method for calculating FFMC throughout the day using hourly weather information, laid out by Van Wagner (1977)*. This basic fuel moisture exchange model is essentially a simple two part model that includes a model for estimating the influence of rainfall along with a basic exponential drying,

$$\frac{\mathrm{mc(t)-EMC}}{\mathrm{mc(t-\delta)-EMC}} = e^{-k\cdot t} \qquad [1]$$

where mc(t) is the moisture content at time t, mc(t-δ) is the moisture content some time δ prior to t, EMC is the equilibrium moisture content and k is a constant equal to the inverse of the fuel layer time lag. This equation holds if EMC and k do not vary over the time interval δ.

Given this simple foundation, Van Wagner's (1977) method for calculating hourly FFMC has been modified to attempt to incorporate the characteristics of the physical environment of surface fuels in open grasslands more closely. This has been accomplished

* Van Wagner's (1977) method is summarized in these proceedings by K.R Anderson (2009) A comparison of hourly fine fuel moisture code calculations within Canada (paper 3A.4)

through the inclusion of explicit models of: fuel temperature in exposed locations, grass equilibrium moisture content, grass fuel particle response times, and rainfall in a canopyless situation. In addition, the time between weather observations (which must be short for fast reacting grassland fuels) has been explicitly included in this formulation of the model.

2.1.1 Fuel temperature

In the absence of direct moisture (from rain or dew for example) forest fuels absorb and lose moisture based on the temperature and humidity in their environment. Fuel temperature on the surface of a forest floor, particularly in an open or low canopy closure forest stands, can be strongly influenced by the amount of direct solar radiation incident upon it. Byram and Jemison (1943) developed a model to derive fuel temperature from screen-level air temperature, solar radiation and wind speed for leaf litter. Their model had two coefficients that could be changed to account for the different physical properties of other fuel types. Van Wagner (1969) followed their approach and developed a new functional form for this same relationship and derived co-efficient values for a number of common forest fuels. Van Wagner's model was

$$T_f = T_a + a \cdot I \cdot e^{-k \cdot W} \qquad [2]$$

Where T_a is ambient air temperature (°C) measured at screen level, W is the wind speed (km/h) measured near the surface of the fuel, I is solar radiation (kW/m^2), and a and k are two constants specific to the fuel type. For grass Van Wagner's estimated coefficients (in the units of this equation) are 35.07 and 0.06215 respectively.

Using this estimate of T_f, a fuel level relative humidity, RH_f can also be calculated using an estimate of the saturation vapour pressure of the atmosphere based on a screen level observation of air temperature and relative humidity. Saturation vapour pressure can be estimated by (Baumgartner et al. 1982),

$$e_S(T) = 6.107 \cdot 10^{\frac{7.5 \cdot T}{237+T}} \qquad [3]$$

From this e, the actual vapour pressure can be calculated because RH=100·(e/e_S). Therefore,

$$RH_f = \frac{RH}{100} \cdot \frac{e_S(T)}{e_S(T_f)} \qquad [4]$$

These values of T_f and RH_f are used in estimating equilibrium moisture content and response time of the grass fuel layer.

2.1.2 Equilibrium moisture content

Cellulose-based materials gain or lose moisture from the atmosphere in an attempt to reach equilibrium with its environmental conditions; this is called the equilibrium moisture content (EMC) and represents a balance between the moisture within the fuel and the moisture in the atmosphere directly in contact with the fuel. There has been extensive study and development of models of EMC for forest litter. This type of experimentation can be carried out in laboratory environments by including litter material in environmental chambers and varying temperature and humidity in a controlled fashion. Nelson (1984) developed a theoretical model for EMC based on a Gibbs free energy concept, which took the form,

$$EMC = \frac{\ln[-\frac{R \cdot T}{M} \cdot \ln(\frac{RH}{100})] - A}{B} \qquad [5]$$

Where R is the gas constant 1.9872, M is the molecular weight of water 18.0153, T is air temperature (in degrees Kelvin), RH is relative humidity (as a percentage) and A and B are constants specific to the fuel. Nelson derived A and B constants that defined both adsorption and desorption curves for a number of common litter types. Anderson (1990) expanded on this work using Nelson's model and derived A and B coefficients for a broad range of materials, including cheatgrass.

Van Wagner (1972) also developed equilibrium moisture content models for a number of common litter types based on laboratory studies using a common functional form. Van Wagner's model for EMC of the pine needles is currently used in the daily and hourly versions of the FFMC model (Van Wagner 1987, Van Wagner 1977). Van Wagner (1972) also developed a model form for grass fuels which has the form,

$$EMC = \left(a \cdot RH^b + c \cdot e^{\frac{(RH-100)}{d}} \right) + 0.27 \cdot (26.67 - T_f) \cdot (1 - e^{-0.115 \cdot RH_f}) \qquad [6]$$

Figure 1 shows the EMC curves for adsorption and desorption using Van Wagner's grass model as well as Nelson's model using A and B parameters derived for cheat grass with a varying RH and under constant temperatures of 15 and 25 °C. The two sets of curves are quite similar. For the purpose of the development of the current model Van Wagner's formulation for EMC was chosen.

In the model formulation used here the model for EMC is thus

$$EMC_D = \left(1.62 \cdot RH_f^{0.532} + 13.7 \cdot e^{\frac{(RH_f-100)}{13.0}} \right) + 0.27 \cdot (26.67 - T_f) \cdot (1 - e^{-0.115 \cdot RH_f}) \qquad [7]$$

$$\mathrm{EMC_W} = \left(1.42 \cdot \mathrm{RH_f}^{0.512} + 12.0 \cdot e^{\frac{(\mathrm{RH_f} - 100)}{18.0}}\right) + 0.27 \cdot (26.67 - \mathrm{T_f}) \cdot (1 - e^{-0.115 \cdot \mathrm{RH_f}}) \qquad [8]$$

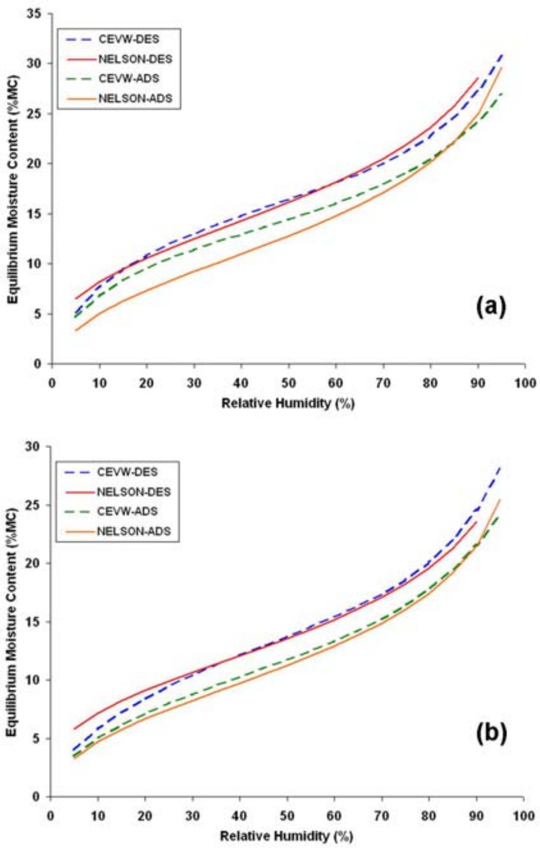

Figure 1: Comparison of the Nelson EMC model (based on Anderson (1990) cheatgrass coefficients) and Van Wagner's (1972) grass EMC model (CEVW). for temperatures of (a) 15 and (b) 25 degrees Celsius.

2.1.3 Response time

Response time of a fuel layer varies with the physical size and arrangement of forest fuels in that layer. Anderson (1990) developed an empirical relationship for response time for fuels based on fuel element surface-to-volume ratio, bulk density and packing ratio. He measured these elements for a number litter types and arrangements and estimated average response times. His estimates for grass give a response time (under his ambient conditions of 26.7 C and 20% RH) of 0.85 hours for desorprtion (drying). The value calculated for adsorption is quite similar, 0.8 hours. This is much faster than the standard FFMC layer in the hourly FFMC model which, at 26.7 °C, 20 % RH and a wind speed at a nominal 2 km/h, would have a response time of 5.72 hours.

Anderson (1990) developed a simple empirical relationship for the influence of temperature on response time, however this was not the main thrust of that research, and as such specific functionality of response time with temperature and relative humidity and wind was not explored in any depth. Van Wagner's development of the FFMC (as described Van Wagner 1977) included a significant influence of these environmental elements on fuel layer response time. This response time function for the hourly FFMC model (based on Van Wagner 1977) is

$$K = 0.0579 \cdot \ln(10) \cdot e^{0.0365 \cdot T} \cdot [0.424 \cdot (1 - R^{1.7}) + 0.0694 \cdot W^{0.5} \cdot (1 - R^8)] \qquad [9]$$

where K is the inverse of response time (in hours), T is temperature (in Celsius), W is wind speed (in km/h) and R is an RH terms equal to RH/100 for the desorption phase and 1-RH/100 for adsorption.

To estimate a new response time function for the grass fuel moisture content model the response time function from the hourly FFMC was scaled by the response time value from Anderson (1990) for cheatgrass; that is, at conditions of 26.7 °C, 20% RH and using a nominal wind speed of 2 km/h (Anderson's nominal conditions) Van Wagner's function for K (inverse response time) is scaled by 0.85/5.72; thus this new value (from equation 10) equates to a response time of 0.85 hours under those standard conditions.

The new value for K_{GRASS}, the inverse of the response time (in hours), for the grass model thus becomes

$$K_{GRASS} = 0.897 \cdot e^{0.0365 \cdot T_f} \cdot [0.424 \cdot (1 - R_f^{1.7}) + 0.0694 \cdot W^{0.5} \cdot (1 - R_f^{8})] \qquad [10]$$

2.1.4 Rainfall influence

The rainfall absorption methodology within the hourly FFMC uses total rainfall and the estimated moisture content of the fine fuel layer before the rainfall to determine the fraction of that rainfall absorbed. However, little research has been carried out on the absorption of rainfall by grass. For simplicity in this model it is assumed that the grass layer has a saturation limit of 250%; this is the limit used the FFMC model and seems a reasonable limit for fine fuels. It is further assumed that all rain that falls on the grass is absorbed up until this saturation limit. The grass layer for this model is given an oven dry weight of 0.3 kg/m^2, the default for grass load in the FBP System. Since the density of water is 1000 kg/m^3, then a 0.3 mm rainfall corresponds to an increase in moisture content of the grass layer of 100% gravimetric moisture content (that is, if the moisture content before rain was 10% then after 0.3 mm rainfall the moisture content would be 110%). Therefore rainfall of approximately 0.8 mm of rain will saturate a completely dry grass layer. Rainfall above this amount is assumed to run-off. Given this very small rainfall saturation limit, the fast recovery time of the layer itself and the strongly increasing variability with moisture content observed in field studies, the assumption that all rainfall that falls is absorbed by the grass layer (up to 250%) seems quite reasonable and unlikely to introduce significant, long-lasting error into a series of hourly moisture content calculations. This simple rainfall effect can be written mathematically then as:

$$\begin{aligned} MC_r &= MC_o + \frac{\text{rain}}{\rho_{FL}} \cdot 100 \\ \text{if } MC_r &> 250 \text{ then } MC_r = 250 \end{aligned} \quad [11]$$

where MC_r is the moisture content of the layer (in %) after rainfall, MC_o is the moisture content of the layer (in %) before rainfall, rain is the amount of rain (in mm) and ρ_{FL} is the nominal fuel load of the layer, in this case chosen to be 0.3 kg/m^2. There is, clearly, no rainfall interception threshold influencing effective rainfall in the calculation in grassland as is present in the daily FFMC model.

2.1.5 Transformation

The fuel moisture models used in the Canadian Forest Fire Danger Rating System have traditionally been transformed from moisture contents to 'code' values such that increasing values of the 'code' indicate increasing dryness, and hence increased fire danger. The transformations used to convert moisture content (mc) to the standard FFMC value are presented in Van Wagner (1987) and represent what is know as the FF-scale. For the sake of continuity, given that forest managers familiar with the FFMC have come to understand this relationship between FFMC and moisture content, the FF-scale will be used in the grass fuel moisture model to convert from moisture content to an equivalent code to the FFMC, which will be named the Grass Fuel Moisture Code (GFMC)

$$GFMC = 59.5 \cdot \frac{250 - mc}{147.2772 + mc} \quad [12]^*$$

$$mc = 147.2772 \cdot \frac{101 - GFMC}{59.5 + GFMC} \quad [13]^*$$

The full calculation method for the grass moisture model is laid out in the Appendix.

2.2. Field sampling

A validation dataset was assembled to test the ability of the new model to estimate moisture content in the surface litter layer in open grass fields. A short campaign of destructive litter moisture sampling was carried out in spring of 2006 at a site outside of Sault Ste Marie, Ontario, Canada. An open site was located near Echo Bay, Ontario (46.48 °N 84.07 °W) was located. This site was completely open, and more than 100 m from any structure or significant stand of trees that might influence shading or wind exposure. The site, an untended farmers field, was composed of large areas of matted field grass (mainly Timothy: *Phleum pratense*) and some areas of standing grass. A standard fire weather station was established on-site, with data recorded at 15 minute intervals. In addition to the standard measurements of air temperature, relative humidity, wind speed and direction at 10 m and rainfall, a LICOR 200S pyranometer was added to the station to record incoming solar radiation on site. The depth of the matted grass layer at this site varied but was approximately 30 cm. Fuel loads at this site, again while variable, were approximately 0.4 kg/m^2.

Destructive sampling was carried out throughout the day at 45 minute to 90 minute intervals depending on weather and time of day as well as logistical constraints. At each sample period six 500 ml tins of grass (approximately 15 grams per sample dry weight) were collected from the top 10 cm of matted grass and six tins of standing grass were also collected. Tins were sealed with tape and stored for later processing in the lab. Destructive sampling was carried out during daylight hours from May 17th to May 25th 2006.

Due to the number of samples taken throughout the day, processing of samples in the lab took place daily. Tins were opened, weight 'wet', then dried for approximately 24 hours at 90 °C, then removed and weight again 'dry'. The weight of each tin was also recorded at this time. Gravimetric moisture content (moisture content by dry mass) was then calculated using the standard method. All moisture contents referred to in this paper are gravimetric moisture (by dry mass) and are presented as percentages.

2.3 Analysis

Observed weather data was used as an input to the grass fuel moisture model described in section 2 to estimate grass moisture during the diurnal cycle. Estimated values of moisture were compared to observed values in the matted layer both graphically and through simple correlation analysis. To contrast with current methods, the hourly FFMC (HFFMC) was also calculated using hourly summaries of the dataset and values compared with observed moisture content.

Since most prescribed burning in Ontario is in matted fuels due to the pack of winter snow the grass moisture model was developed to track moisture in this matted layer. The methodology used in destructive sampling however provided paired samples of matted and standing grass. Mean differences between these paired observations were

* This is a modification of the accuracy in the original equations for the FF-scale conversion presented in Van Wagner (1987). The increase in accuracy in the constant (originally defined as 147.2) is necessary, when a large number of conversions back and forth between moisture content and 'code' value are carried out, to avoid a systematic bias in the standard calculation methodology.

calculated, and the difference between these two layers examined as a function of moisture content of the layer itself.

3. RESULTS

In the diurnal sampling at the Echo Bay site, 593 moisture samples were collected over the 8 day period yielding 61 moisture content means for the matted fuels. Moisture content means in the matted grass for the sample periods ranged from 5.2 % to 182 %. Moisture content means in the standing grass for the sample period ranged from 6.7% to 30%. Significant rain fell all day on May 18 (8.5 mm) and in the evening on May 20 and early morning hours of May 21 (3.6 mm).

A plot of predicted moisture content from the grass fuel moisture model versus observed moisture content is shown in Figure 2a. A similar plot of predicted moisture content based on the hourly FFMC model versus observed moisture is shown in Figure 2b. Simple correlations of predicted and observed in these two datasets were 0.87 (n=60) for the grass moisture model and 0.72 (n=51) for the HFFMC model. These correlation should be interpreted with caution however as each data point is not truly independent.

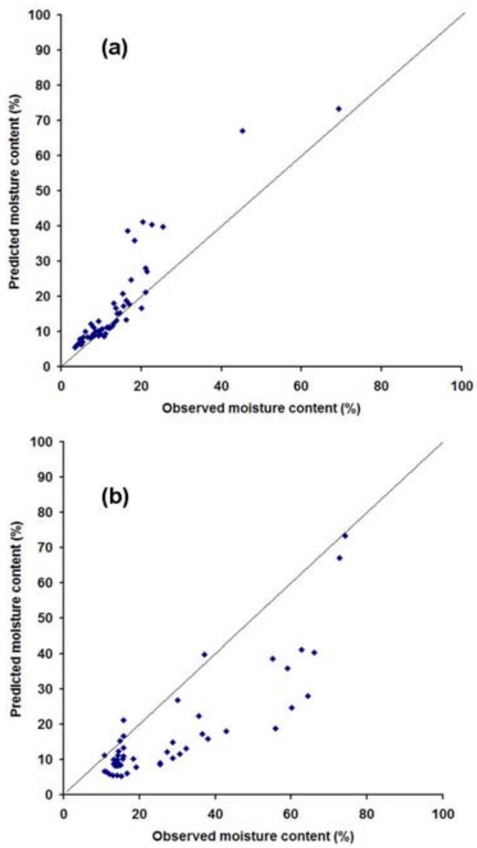

Figure 2: Predicted and observed moisture content from (a) the new grass fuel moisture model and (b) the standard hourly FFMC model.

A time series of the moisture content means observed at the Echo Bay site is shown as points in Figure 3a. This figure also includes the time series from the HFFMC and GFM model. Figure 3b shows the same plot with only the lower 50% of moisture on the coordinate axis to examine fit of the model at the dry end in more detail.

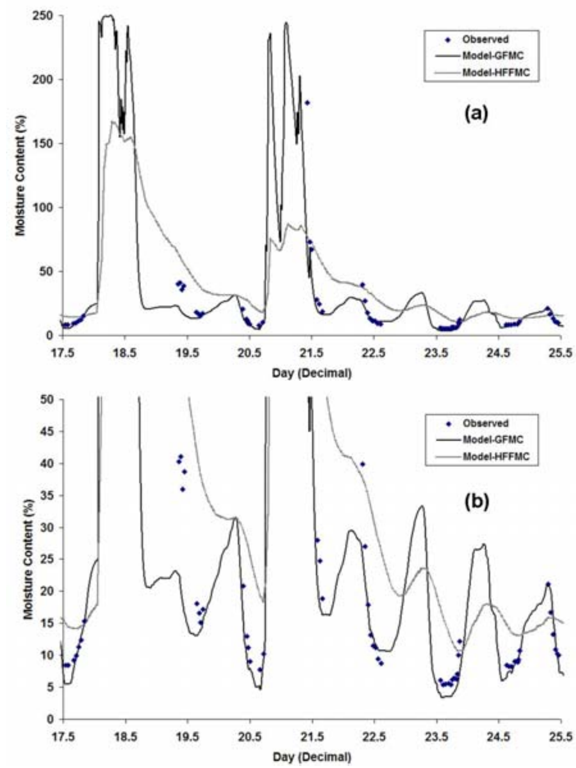

Figure 3: Time series of observed and modelled moisture contents (modelled from both HFFMC model and GFM model) for the fuel period of destructive grass moisture sampling. Plot (a) is shows the full range of moisture content, while (b) shows the same data focusing only on points below 50%.

A plot of the moisture content difference between matted grass and standing grass (MC_{MATTED} – $MC_{STANDING}$) against moisture content observed in the matted grass is shown in Figure 4a for the entire range of observations. Figure 4b shows this plot for moisture contents in the matted grass less than 30.

4. DISCUSSION

The plots in Figure 2 show that both the Hourly FFMC model (Figure 2b) and the new grass fuel moisture model (Figure 2a) capture a reasonable amount of variation observed in the validation dataset. The hourly FFMC tended to over predict moisture, that is predict conditions that were wetter than observed; this was expected given that the HFFMC assumes it is in a closed canopy pine stand, an environment that would be wetter on most days than open stand conditions. The new grass fuel moisture model was closer to the line of equivalence, however did tend to under predict moisture at the low end. There are also a cluster of points around predicted values of 40% moisture content. This group from the morning of May 19th and after the 8.5 mm rainfall on the 18th and the model has missed something significant that influenced moisture content that morning (perhaps dew or standing water still on the grass layer).

An examination of the time series of HFFMC over the 8 day sampling window (Figure 3), showed the systematic over-prediction of the moisture content in the litter layer quite clearly; what was also clear from this plot was the limited diurnal variation in this value and the late minima observed in the diurnal trend. The grass moisture mode time series tracked the absolute value of moisture content in the grass layer and the range in diurnal variation quite well. In addition it seemed to capture the timing of the fall and rise in moisture at the beginning and end of the drying day. At the driest point of the day the model seemed to have a tendency to under-predict the moisture content slightly, though its agreement overall at these minima was far closer that of the HFFMC model (though again this is expected given the design of the model). This under-prediction could be a result of errors in the equilibrium moisture content formulation at this lower moisture, or perhaps errors in the fuel temperature model and its subsequent application to equilibrium moisture content.

The difference between moisture content of matted grass (most common in the spring in Ontario) and standing grass was quite interesting. Standing grass, with its vertical orientation and small horizontal profile to the sky did not seem to absorb any real significant amount of the rainfall that occurred during this study (moisture contents did not rise above what one would estimate the fibre saturation point in this fuel type; the highest observed moisture content was 30%. This observation of peak moisture content was the first observation after the end of a 3.6 mm rain event over the previous day and corresponded to a mean moisture content of 182 % in the matted grass. Figure 4 shows that when the grass surface layer is moist (after rain or in early morning after overnight wetting) standing grass is generally much drier than matted material; during clear drying days, when solar radiation is playing an important role in heating the fuel, the matted layer can dry to values several percentage points lower than standing grass however. This extra drying in the matted layer is due to its orientation and its exposure to the fuel heating influences of incoming solar radiation.

For users of the FWI System there are some important differences between hourly FFMC and the grass model to emphasize. Table 1 shows the response of both the hourly FFMC and the hourly grass fuel moisture model to a rain shower of 5 mm during a good drying day. While an experienced user of the FWI System would know it would take 2-3 days for the FFMC to recover to pre-rain values (a reasonable time lag in a closed canopy boreal stand) the grass fuel moisture model recovers to moisture contents that would sustain fire spread in 203 hours. This rapid recover of grassland fuel moisture to rain has indeed been observed by researchers in Australia (Cheney and Sullivan 2008).

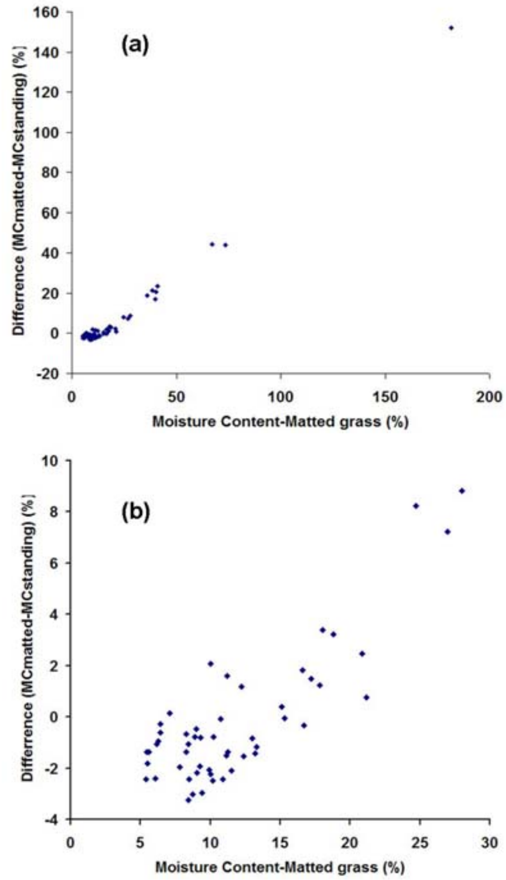

Figure 4: Plots of the difference between paired samples of matted and standfing grass as a function of moisture content of standing grass. Plot (a) shows the full range of data and plot (b) shows only those points below 30% moisture in the matted layer.

Table 1: A comparison of the recovery rate of the Hourly FFMC and the new grass moisture model on a hypothetical day with rain at 10 am. The moisture content prior to rain was 10% and it is a bright sunny day.

Time	T (°C)	RH (%)	WS (km/h)	Rain (mm)	Moisture content /moisture code	
					HFFMC model	Grass model
1000	25	90	10	5.0	103%/35	88%/41
1100	25	25	10	0.0	86/42	30%/75
1200	25	25	10	0.0	72%/48	15%/86
1300	25	25	10	0.0	61%/54	11%/90
1400	25	25	10	0.0	50%/60	10%/91
1500	25	25	10	0.0	42%/65	10%/91
1600	25	25	10	0.0	37%/69	10%/91

Further work

The model will be further validated against a dataset of grass moisture content observations that have been collected by the Great Lakes Forest Centre's Fire Research Unit as part of a program of fire behaviour observation during grassland prescribed burns in southern and central Ontario over the past decade. In addition, because the majority of fire weather stations operated by fire management agencies do not currently report solar radiation with their observations, methods will be developed to estimate diurnal solar radiation from latitude, longitude and date in combination with a standard estimate of sky cover.

5. SUMMARY

A new model tracking moisture content in open fully-cured grass fuels has been developed for the Canadian Forest Fire Danger Rating System. This new model is based on the structure of the Fine Fuel Moisture Code model within the Canadian Forest Fire Weather Index System, but also incorporates the influence of solar radiation on the fuel layer. This leads to a fast reacting fuel layer (with response times on the order of 1 hour in typical spring conditions). Observations of grass moisture from the field shows that the new model tracks moisture content much more closely than the existing hourly Fine Fuel Moisture Code. Both absolute value of moisture content and the timing of important diurnal changes are captured reasonably well by the model.

6. REFERENCES

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Appendix

The flow of calculation of the grass fuel moisture content and grass fuel moisture Code (GFMC) is as follows. Equation numbers are given as they have appeared in the paper.

Inputs:
T : temperature in degrees Celsius
RH: relative humidity in %
W: wind speed recorded at 10 metres in the open in km/h
rain: rainfall in mm
I_{SOL}: solar radiation in kW/m^2
ρ_{FL} : 0.3 kg/m^2
t: the time step between the previous calculation of moisture content and the current calculation (in hours).
$GFMC_{OLD}$: the Grass Fuel Moisture Code at the previous time step (unitless)

Step	Calculation
1	$MC_{OLD} = 147.2772 \cdot \frac{101 - GFMC_{OLD}}{59.5 + GFMC_{OLD}}$ [13]
2	If rain>0 then {assume rain occurred at the start of the time step} $MC_r = MC_{OLD} + \frac{rain}{\rho_{FL}} \cdot 100$ [11] if $MC_r > 250$ then $MC_r = 250$ $MC_{OLD}=MC_r$ {reset MC_{OLD} to the rain adjusted value } End if
3	$T_f = T + 35.07 \cdot I_{SOL} \cdot e^{-0.06215 \cdot W}$ [2]
4	$e_S(T) = 6.107 \cdot 10^{\frac{7.5 \cdot T}{237+T}}$ [3]a $e_S(T_f) = 6.107 \cdot 10^{\frac{7.5 \cdot T_f}{237+T_f}}$ [3]b
5	$RH_f = \frac{RH}{100} \cdot \frac{e_S(T)}{e_S(T_f)}$ [4]
6	$EMC_D = \left(1.62 \cdot RH_f^{0.532} + 13.7 \cdot e^{\frac{(RH_f - 100)}{13.0}}\right) + 0.27 \cdot (26.67 - T_f) \cdot (1 - e^{-0.115 \cdot RH_f})$ [7]
7	$EMC_W = \left(1.42 \cdot RH_f^{0.512} + 12.0 \cdot e^{\frac{(RH_f - 100)}{18.0}}\right) + 0.27 \cdot (26.67 - T_f) \cdot (1 - e^{-0.115 \cdot RH_f})$ [8]
8a	If $MC_{OLD}>EMC_D$ then {the fuel is drying} $R_f=RH/100$ $K_{GRASS} = 0.897 \cdot e^{0.0365 \cdot T_f} \cdot [0.424 \cdot (1 - R_f^{1.7}) + 0.0694 \cdot W^{0.5} \cdot (1 - R_f^{8})]$ [10] $MC = EMC_D + (MC_{OLD} - EMC_D) \cdot e^{-K_{GRASS} \cdot t}$ End if
8b	If $MC_{OLD}<EMC_W$ then { the fuel is wetting } $R_f=(100-RH)/100$ $K_{GRASS} = 0.897 \cdot e^{0.0365 \cdot T_f} \cdot [0.424 \cdot (1 - R_f^{1.7}) + 0.0694 \cdot W^{0.5} \cdot (1 - R_f^{8})]$ [10] $MC = EMC_W + (MC_{OLD} - EMC_W) \cdot e^{-K_{GRASS} \cdot t}$ End if
8c	If $EMC_W \leq MC_{OLD} \leq EMC_D$ then { in between the EMC curves $\therefore$ maintain moisture constant } $MC=MC_{OLD}$ End if
9	$GFMC = 59.5 \cdot \frac{250 - MC}{147.2772 + MC}$ [12]