Field Evaluation of a Moisture Content Model for Medium-Sized Logging Slash

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Abstract

A moisture content model for medium-sized logging slash was developed by Van Wagner from field data collected in three-year old jack pine slash averaging 4 cm in diameter. Field tests of this model and its tentative adjustments for slash age and diameter range were conducted by the authors in first-year and second-year old white spruce-subalpine fir logging slash of various diameters. Tests of the model and its assumptions were conducted using both in-situ, roundwood slash samples exposed for the season in trays and weighed daily, and destructive samples stratified by depth increment, taken on a weekly basis. Correlation of this independent data set with Van Wagner's model predictions is presented, along with some possible modifications for these species and age differences and size range from two to ten cm.

The objective of this slash moisture modeling research is to further develop the Canadian Forest Fire Danger Rating System as an aid to quantifying fire danger and behavior in forest cutovers. Eventual use of slash moisture models in prescribed fire decision-aids to improve predictions of slash fuel consumption in silvicultural prescribed burns is discussed.

Résumé

Van Wagner a élaboré un modèle de teneur en humidité des résidus d'exploitation de grosseur moyenne à partir de données recueillies dans des parterres de coupe jonchés de rémanents de pin gris de 3 ans d'un diamètre moyen de 4 cm. Les auteurs ont procédé à des essais au champ de ce modèle et tenté de l'ajuster en fonction de la gamme d'âges et de diamètres des rémanents dans un parterre de coupe à résidus d'épinette blanche-de sapin subalpin de l'année en cours et d'un an à diamètre variable. Le modèle et ses hypothèses ont été vérifiés à l'aide d'échantillons de bois ronds rémanents se trouvant sur le terrain et placés dans des plateaux à l'air libre pendant toute une saison et pesés quotidiennement et à l'aide d'échantillons en décomposition stratifiés selon l'accroissement en profondeur mesuré à chaque semaine. Les auteurs présentent une corrélation entre cet ensemble de données indépendantes et les prévisions du modèle de Van Wagner ainsi que certaines modifications possibles à apporter selon les espèces et les différences d'âge et une gamme de dimensions allant de 2 à 10 cm.

L'objectif de ces recherches sur la modélisation de la teneur en humidité des résidus d'exploitation est d'améliorer la Méthode canadienne d'évaluation des dangers d'incendie de forêt pour aider à quantifier le danger et le comportement du feu dans les parterres de coupe. Les auteurs examinent l'utilisation éventuelle des modèles de teneur en humidité des rémanents par les systèmes d'aide à la décision lors de brûlages dirigés afin de mieux prédire la consumation de combustibles des rémanents lors de brûlages dirigés réalisés à des fins d'aménagement sylvicole.

Introduction

At present, the two main subsystems of the Canadian Forest Fire Danger Rating System (CFFDRS), the Fire Weather Index (FWI) System and the Fire Behavior Prediction (FBP) System (Stocks et al. 1989), do not contain fuel moisture models for woody components of logging slash.

To address the need for improved measurement of fire danger in forest cutovers, Van Wagner (1987) developed a model to predict moisture content in 4 cm diameter logging slash. Conceptually, the model is a moisture budget driven by standard daily fire weather inputs.

Wetting and drying phases were developed separately from field data collected by Stocks and Walker (1972) in three year old jack pine (Pinus banksiana Lamb.) logging slash in Ontario. Van Wagner (1987) discussed generalizing the model for a range of slash wood ages and sizes, using earlier data from Lawson (1985) for west coast Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) and western red cedar (Thuja plicata Donn) to develop a tentative adjustment for age.

The purpose of this paper is to evaluate the Van Wagner (1987) model using new test data for first-year and second-year white spruce (Picea glauca (Moench) Voss) - subalpine fir (Abies lasiocarpa (Hook.) Nutt) logging slash collected during 1987 and 1988 field seasons near Prince George, British Columbia.

Alternatives to mathematical weather-dependent models for woody fuel moisture monitoring, including

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direct weighing of B.C. Forest Service fuel moisture sticks[1] and direct readout moisture meters, were also evaluated in this study and are briefly discussed.

Literature Review

Simard et al. (1984) reported fair correlation between certain Canadian and U.S. fuel moisture models and some sizes and conditions of jack pine slash wood. Their regression equations for 5 cm slash with bark included Duff Moisture Code (DMC) and Fine Fuel Moisture Code (FFMC) components of the FWI System and produced R^2 of 0.73 with a standard error of 4.2, a slightly better relationship than was achieved using U.S. round wood moisture models. Van Wagner's (1987) goal was a model developed specifically for medium-sized logging slash, in order to improve prediction accuracy. Sufficient Canadian data was not then available to test it much beyond the data set used to develop the model. An existing data set (Lawson 1985) was available for 1 to 3 cm mixed Douglas-fir and western red cedar slash in its first summer of drying on a coastal British Columbia site. Van Wagner (1987) did a partial test of his proposed slash age correction (reduced rainfall effect for first year and second-year slash) using this data.

Subsequently, Trowbridge and Feller (1988) reported good relationships between fine (less than 1 cm) lodgepole pine (Pinus contorta Dougl.) slash moisture and the FFMC, pointing out the necessity of allowing the slash to cure sufficiently (about 3 snow-free months) after cutting before its moisture content can be predicted adequately by such models as FFMC. They also reported high correlation between B.C. Forest Service fuel moisture stick weights and FFMC as predictors of fine slash moisture.

A study currently in data analysis phase (Péch 1988) will provide additional information on continuous wetting and drying over a range of medium slash diameters. This should help resolve some of the problems in using once per day sample weighings to derive daily wetting and drying rates, which hindered both Van Wagner's model development and this present test.

Electric moisture meters of the conductance (resistance) type were thoroughly discussed by James (1988), noting acceptable accuracy is possible at moisture contents less than 30 percent and that readings are affected by such factors as wood species, temperature, moisture distribution and operator skill. Blank et al. (1983) reported field test results of one such meter whose readings were well correlated with observed fuel moisture of 1-inch dead jack pine branchwood.

Methods

Field trials were conducted to evaluate performance of the Van Wagner model in predicting daily moisture content of slash with different species, ages and sizes to those used in its development. Some of the assumptions used in the basic 4 cm slash model and adjustments for other ages and sizes of slash were tested in this new field study, in accordance with Van Wagner's suggestion that, while the basic 4 cm slash model was "moderately sound," his proposed extensions for age and size were "tentative", and required further field testing.

In general, the approach to the model evaluation field trials was similar to that used to gather the original data. White spruce-subalpine fir slash from the March, 1987 clear cutting of a 1960's selectively logged (but poorly regenerated cutover) site near Stony Lake in the Prince George East Forest District of central British Columbia (lat. 53°27'N, long. 121°54'W, elevation 970 m) was selected as the study material. The slash was sampled for moisture content during the 1987 (first year) and 1988 (second year) field seasons. Samples of several diameters of slash of each of the two species were set in galvanized wire-screen trays 30 cm square in an open level area and weighed daily, in the early afternoon. At the end of each season, the tray material was oven-dried and the daily moisture contents calculated. As well, weekly destructive samples of both species for several diameters were stratified by depth specifically to evaluate the "dry centre" assumption used in the model and its extensions. Standard daily fire weather observations (Turner and Lawson 1978) required for calculating the components of the FWI System and the Van Wagner model were recorded at a standard forest fire weather station adjacent to the fuel moisture site. In addition to these noon (local standard time) observations of temperature, relative humidity, 10-minute average wind speed (10 m height) and 24-hour rain, a second station recorded hourly average values of these parameters.

Tray data were collected for white spruce branch and bole wood and subalpine fir branchwood of the same diameter ranges, 2.5 to 5.0 cm, as in the original model; in addition, two fine size classes, 0.1 to 1.0 cm and 1.1 to 2.0 cm, were studied, as were four specific medium diameters, 2.0, 4.0, 6.0, and 10.0 cm. Cut ends and branch cuts of all pieces 2.0 cm and over were double-sealed with melted paraffin at the start of each season. The following characteristics and assumptions in the Van Wagner model were tested across this wide range of fuel size for the two species and ages, separately:

1. Daily drying rate follows a negative exponential model, equation (1), mostly dependent on initial fuel moisture content, and only weakly dependent on daily noon weather variables, temperature (T), relative humidity (H), and wind speed (W).

Van Wagner revised his equation (2) drying rate subsequent to the original published version (Van Wagner 1987); it is reproduced below for current reference:

$$(M - E)/(Mo - E) = e^{-kt} \tag{1}$$

$$k = 0.023\ e^{0.0182\ T}\ [1-(H/100)^{1.7}](0.1+0.0151\ W^{0.5})\ (Mo-5)^{1.2} \tag{2}$$

where k is logarithmic daily drying rate,

Mo is initial moisture content (%),
M is final moisture content (%),
E is equilibrium moisture content (EMC)
t is time (days)

The negative exponential drying model (equation 1) was unchanged but evaluated in this study for the suitability of the constant value of 5% for EMC chosen by Van Wagner. Relative contributions of Mo and noon weather measurements to the prediction of observed daily drying rate were evaluated using multiple regression analysis. Correlation of predicted drying rate (xk) from the model and observed drying rate (k) was checked, along with the linearity of the relationship.

2. Daily response to rain, while in reality is a combination of wetting due to rain, followed by subsequent drying after cessation of rain, can be approximated by a model driven by daily rainfall amount and initial fuel moisture content.

This study suffered from the same problem as Van Wagner's in that once-daily measurements of fuel moisture, while taken at approximately the same time each day, represented various combinations of wetting and drying times. This precluded a rigorous analysis of the "gross" rain effect, so only correlations with observed "net" change in moisture content (ΔM) (some negative) could be checked against the net change in moisture following rain plus subsequent drying predicted by the model (cM)[2].

3. Drying and wetting rates for medium-sized slash over a wide range of diameters follow a model suited to "dry-centre" internal distribution of moisture within the piece, such that the outer layer is responsible for most of the wetting and drying response to current weather conditions. The dry-centre mode supports the theory of faster drying rates than would be expected for uniform distribution of moisture with depth, or for "wet-centre" mode.

The destructive sampling of slash of both species for the "dry-centre" evaluation was done on a dry day (no rain in last 24 h) every four or five days. Two samples of each species in three diameters (3, 6 and 10 cm) were cut from branchwood or bole wood of the fully exposed slash used to supply the tray material. Cross-sections were stratified and split by 2 cm depth increments from top to bottom of the piece (1 cm increments for 3 cm diameter samples). Each depth stratum for each sample was separately oven-dried for moisture content determination. The whole data set was analyzed for trends, separately by year, season, species and diameter.

4. An extension of the model to diameters other than the 2.5 to 5.0 cm slash size used in its development has been suggested, based on the assumption that both drying rate and rainfall effect vary with the square root of diameter. The strengths of our observed relationships of drying and wetting rates with slash size were evaluated using log-log slope analysis.

5. Taking 60% and 80% of the total rain effect on daily slash fuel moisture for first and second-year slash respectively had been suggested for trial use as an age adjustment to the basic model developed for three-year old heavily checked slash. This approach had been tentatively supported by Van Wagner's test against an independent data set (Lawson 1985) of cured first-year slash of different species and size. We evaluated the model's rainfall effect with the age adjustments suggested by Van Wagner (1987), over our range in diameters, using regression analysis against our observed rainfall effects on fuel moisture.

6. Moisture content of very fine slash less than about 2 cm diameter can be better predicted by models such as FFMC and fuel moisture sticks, probably because as size decreases, the slash spends more time near its EMC and the internal moisture distribution becomes more uniform. The FFMC particularly, with variable EMC and k that remains constant with M would be expected to be superior to the present model for very fine slash. Regression analysis was used to evaluate the Van Wagner slash model, FFMC and fuel moisture sticks as predictors of moisture content of 0.1 to 1.0 cm and 1.1 to 2 cm subalpine fir slash.

An additional objective of the study, to be briefly discussed, was to investigate the viability of direct fuel moisture content determination using resistance-type meters as an alternative to weather-dependent models for medium slash. While typical performance of these meters has been reported in several earlier studies, an investigation of their usefulness in medium and large slash moisture determination above fibre saturation was undertaken as an adjunct to the present study.

In 1988, a Triton-2000[3] digital wood moisture meter was used in a comparison trial of accuracy against standard oven-drying for fuel moisture determination. The sample material was the 6 and 10 cm spruce and subalpine fir slash sampled approximately weekly for the "dry-centre" assumption test. Each 2 cm-deep increment from each 6 and 10 cm diameter piece was split and read with the moisture meter, using three separate 1 cm insertions and readings of the double-pinned probe into the cross section. Three meter readings were averaged for comparison regressions against oven-dry fuel moisture contents of each piece. No corrections were applied to the meter readings for species or temperature.

Results and Discussion

The regression of predicted daily moisture content vs. observed tray moisture content using Van Wagner's (1987) model suggested adjustments were needed in the model's extension for slash age and diameter for white spruce-subalpine fir slash. Correlation coefficients were poor for first-year slash of the same 2.5 to 5.0 cm sizes used to develop the basic model, but improved for second year slash (highly significant[4] $R^2 = 0.61$ and 0.52 for spruce and subalpine fir respectively, Table 1). Of the first-year slash sizes, only fine slash (0.1 to 1.0 cm) was well correlated with the model ($R^2 = 0.76$), whereas all the medium slash sizes up to 6 cm were highly correlated in the second year (R^2 in the 40's and 50's). Ten cm slash moisture was not correlated with the model either year.

Taking our study objectives in turn:

1. Predicted drying rates (xk) were poorly correlated with observed daily drying rates (k) for all sizes from 2 to 5 cm for first-year slash. R^2 increased to only 0.33 for second-year 4.0 cm subalpine fir slash. Correlations improved somewhat for second-year slash of (>5 cm) larger diameters, with a highly significant R^2 of 0.60 for 10 cm white spruce (Table 1) and linear relationship. One problem with modelling current year slash moisture is that the first season has a combination of "green" and "cured" drying periods with markedly different drying rates.

In this study, first-year slash appeared to cross the transition from green to cured about mid-July, by which time most slash diameters had dried down to fibre saturation (about 30%) or below, in spite of three consecutive days of heavy rain totalling 65 mm between July 6 to 8 (Fig. 1).

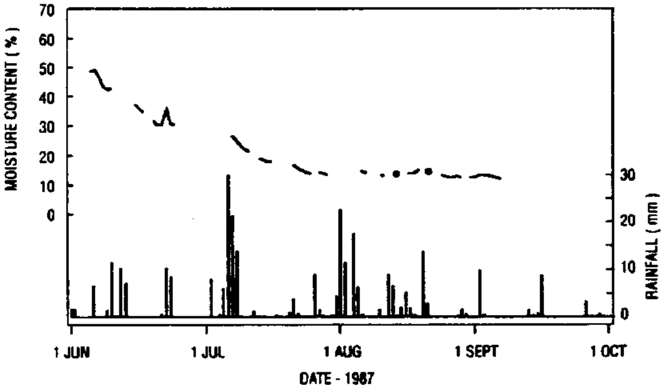

FIG 1. Observed seasonal moisture content change of first-year 2.5 - 5.0 cm white spruce slash in trays with rainfall amount.

Table 2. Ranges and means of 1987 and 1988 noon (Pacific Standard Time) weather observations and medium slash fuel moistures of white spruce and subalpine fir samples exposed in trays in the open.

Parameter	First-Year[1] Min	First-Year[1] Max	First-Year[1] Mean	Second-Year[1] Min	Second-Year[1] Max	Second-Year[1] Mean
Temperature (°C)	6.7	28.1	18.3	8.1	26.5	16.8
Relative Humidity (%)	24	86	50	25	83	53
Wind Speed (km/h)	0	26	8.4	1	25	10.2
Rain (mm)	0.3	30	2.9	0.3	19	2.0
Spruce 2-5 cm (%)	12	49	21	17	40	29
Subalpine fir 2-5 cm (%)	14	42	22	23	42	32

[1] Statistics for sampling periods only: June 8 - Sept. 7, 1987; May 31 - Sept. 1, 1988.

The two seasons studied were quite variable in terms of weather conditions and tray fuel moisture which was useful for the model evaluation. Ranges of these variables are given in Table 2 for first-year and second-year slash. The two seasons were similar in that both had maximum consecutive rainless periods of 8 days and maximum consecutive rainy periods of 7 days during the fuel moisture measurements.

Of the three weather variables, only T was correlated to any degree with the observed k, with R^2 in the 0.20's and 0.30's for second-year slash. Combining Mo with the weather variables (T, H and W) produced highly significant R^2 of 0.73 and 0.71 of 0.73 and 0.71 for second-year 0.1 to 1.0 cm and 1.1 to 2.0 cm fine slash, respectively). For the medium slash sizes, the combined variable R^2 remained in the 0.30's and 0.40's.

2. The rainfall phase (cM) was poorly correlated with observed daily rainfall effects (ΔM) for all sizes of first-year slash (R^2 in the 0.30's), but was better in second-year slash, with R^2 generally in the 0.40's and highly significant ($R^2 = 0.70$) for 2 cm subalpine fir. ΔM's were not significantly correlated with rainfall amount for first or second-year medium slash sizes. ΔM's were also not well correlated with Mo (previous day's observed moisture content) for first year slash, and only moderately and negatively correlated with Mo for second-year slash (R^2 in 0.30's). The highest correlations were found for one-year old fine slash in the two smallest diameter ranges with R^2 in the 0.50's.

Again, the problem of slash curing in the current year was partially responsible for the poor relationships found between wetting effects and rainfall amounts. "Green" slash with diameters greater than 1 cm wets and dries somewhat independently of rainfall and daily weather up to the middle of July in the first year; a model of the wetting and drying process would appear to be of little utility until the slash material reaches the "cured" stage and is more responsive to a changing weather environment.

As found by Van Wagner (1987), this study indicated that most small rains (up to 2 mm) produced negative ΔM's on a "net" basis. Overall the rainfall effect in Van Wagner's model was judged to be too large, especially as diameter increased, although a plot of cM vs ΔM was linear.

Multiple regressions of ΔM vs. Mo, rainfall duration and total daylight hours since rain stopped showed that except for the finest size slash, total daylight hours was the strongest variable (combined R^2 from 0.29 to 0.82). Substituting for rain duration other "time since rain stopped" variables, i.e., total hours and total drying hours since rain stopped, improved R^2 to the 0.70's and 0.80's, with Mo and total daylight hours the most significant variables. The exception was the finest size slash, in which a highly significant R^2 of 0.86 with rainfall duration, dropped to 0.68 without it. For prediction of medium slash rainfall effect, time since

Table 1

Linear regression statistics of slash model outputs (Van Wagner 1987) against observed first- and second-year slash samples exposed in trays in the open, by species and diameter

Model feature	Species	Diam. (cm)	First-year slash					Second-year slash				
			Days (n)	Y-intercept	Slope	R^2	RMSE[7]	Days (n)	Y-intercept	Slope	R^2	RMSE
xM[1]	B[4]	0.1-1	52	7.1	0.12	0.23	2.6				NS	
	B	1.1-2	52	4.9	0.52	0.35*	4.7	52	-0.93	0.66	0.76*[6]	3.1
	S[5]	2	52	11	0.29	0.20	5.4	52	-3.9	0.52	0.48*	4.7
	B	2	52	5.5	0.52	0.23	5.2	52	-3.7	0.50	0.59*	4.1
	S	2.5-5				NS[8]		52	-5.9	0.91	0.61*	3.9
	B	2.5-5				NS		52	-14	1.1	0.53*	4.3
	S	4				ND[9]		52	-8.9	1.1	0.56*	4.0
	B	4				ND		52	-6.9	0.83	0.53*	4.2
	S	6				NS		52	-7.7	1.1	0.50*	4.0
	B	6				NS		51	-28	1.4	0.47*	4.1
	S	10	52	10	0.34	0.16	4.6	51	3.1	0.82	0.25	4.4
	B	10	52	11	0.29	0.13	4.7				NS	
xk[2]	B	0.1-1				NS					NS	
	B	1.1-2				NS		21	0.03	0.51	0.48	0.04
	S	2				NS					NS	
	B	2				NS					NS	
	S	2.5-5				NS					NS	
	B	2.5-5				NS					NS	
	S	4				ND		21	0.04	0.67	0.33	0.03
	B	4				ND		21	0.04	0.56	0.34	0.03
	S	6				NS		21	0.04	0.53	0.34	0.02
	B	6				NS		19	0.03	1.2	0.44	0.02
	S	10				NS		21	0.03	0.89	0.60*	0.01
	B	10				NS		19	0.04	0.92	0.40	0.02
cM[3]	B	0.1-1				NS					NS	
	B	1.1-2				NS					NS	
	S	2				NS		19	10	1.3	0.54	5.7
	B	2				NS		19	9.4	1.2	0.71*	4.6
	S	2.5-5				NS		19	7.2	1.4	0.56	4.2
	B	2.5-5				NS		19	7.9	1.4	0.39	4.8
	S	4				ND					NS	
	B	4				ND		19	6.6	1.2	0.47	4.0
	S	6				NS					NS	
	B	6				NS		19	5.5	1.7	0.42	3.5
	S	10				NS					NS	
	B	10				NS					NS	

[1] Predicted moisture content

[2] Log. drying rate

[3] Net ΔM after rain

[4] subalpine fir

[5] white spruce

[6] * denotes significant at 0.0001 level; all others significant at 0.01 level or better.

[7] root mean square error

[8] not significant at 0.01 level or better

[9] no data

rain stopped was such a significant variable that it would be difficult to operate a once-a-day scheme that cannot apportion between drying and wetting hours. The advent of hourly fire weather data recording systems now makes more complex fuel moisture models, like Van Wagner's (1977) hourly version of FFMC operationally feasible.

3. Van Wagner's "dry-centre" assumption of internal moisture distribution[5] to support daily drying rates higher than would be expected for uniform or "wet-centre" distribution was not found to be consistent by the current study results of the proportional frequencies and persistence of the dry-centre pattern by species, diameter and season (Table 3). Only 3 cm subalpine fir followed dry-centre throughout the current year, but the trend did not persist beyond mid-July of the second year. Ten cm subalpine fir did not follow dry-centre mode in either year, while 6 cm fir followed the pattern only in the first spring. Only 3 cm spruce (although samples were not available for last half of the second year) exhibited the dry-centre pattern in the first spring.

Persistence of the dry-centre assumption results indicated that only diameters < 6 cm in both species showed consistent trends, with a maximum of 7 days for the longest streak (3 cm first-year subalpine fir).

4. Van Wagner's proposed extensions of his 4 cm diameter model to other diameters are based on his tentative conclusion with partial support from other studies, that both drying rate and rainfall effect decreased with the square root of diameter up to 10 cm. He contrasted his findings with those of Nelson (1969), for wet-centre drying and the U.S. fuel moisture models (Bradshaw and Deeming 1983), whose timelags varied as the square of diameter.

In this study, slope of logarithmic drying rate (k) vs. logarithm of diameter varied from -0.61 to -0.87 (Table 4), depending on species and age of slash, supporting a stronger decrease in drying rate with increasing diameter than assumed in the Van Wagner model, although it is a much gentler slope than indicated in the U.S. references.

We found also that rainfall effect decreased with increasing diameter much more steeply than Van Wagner's slope of -0.5. Our log-log slopes ranged from -1.22 to -1.36 (Table 4), depending on species and age, more consistent with Van Wagner's (1987) concept that rainfall effect, if moisture were distributed evenly throughout the piece, should be proportional to the surface-to-volume ratio of the piece (2/radius). Van Wagner accounted for his gentler slope with diameter

Table 3

Proportional frequencies and persistence of the "dry-centre" assumption in destructively sampled slash by species, diameter, and season.

Sample Year	Slash Species	Slash Diameter (cm)	Proportional Frequencies[1]: Season: Spring[2] (%)	Spring[2] Total Sample Days	Summer[3] (%)	Summer[3] Total Sample Days	Total (%)	Total Total Sample Days	Persistence of Trend: No. of Streaks[4]	Longest Streak[5] (days)
1	B[6]	3	83	12	68	19	74	31	2	7
1	B	6	83	12	41	17	59	29	2	5
1	B	10	0	11	7	14	4	25	0	0
1	S[7]	3	46	11	29	21	34	32	2	5
1	S	6	20	10	11	19	14	29	0	0
1	S	10	30	10	13	16	19	26	0	0
2	B	3	70	10	29	14	46	24	2	5
2	B	6	20	10	43	14	33	24	1	4
2	B	10	0	10	0	14	0	24	0	0
2	S	3	40	10	ND[8]		ND		0	0
2	S	6	0	10	ND		ND		0	0
2	S	10	0	10	ND		ND		0	0

[1] Proportion of total sample days which exhibited the dry-centre pattern $\left(\frac{\text{no. of days with dry-centre}}{\text{Total no. of sample days}} \times 100.\right)$

[2] Defined here as the period from the start of fuel moisture sampling to July 15.

[3] Defined here as the period from July 16 to the end of fuel moisture sampling.

[4] A streak is a period of three or more consecutive days exhibiting the dry-centre pattern.

[5] The maximum number of days in any one streak.

[6] Subalpine fir.

[7] White spruce.

[8] ND - no data.

Table 4. Logarithmic slopes of observed drying rates (k) and net rainfall effects (ΔM) against log. diameter by species and age of slash.

Species	Year	Slope	R^2	Diam. range (cm)	No. Trays (n)
1. log. drying rate (k) vs. log. diameter					
B	1	-0.61	0.95	0.3-10	6
B	2	-0.79	0.93	0.3-10	11
S	1	-0.87	0.98	2.0-10	4
S	2	-0.82	0.77	2.0-10	9
2. log. net rainfall effect (ΔM) vs. log. diamter					
B	1	-1.22	0.87	0.3-3.3	4
B	2	-1.23	0.28	2.0-6	6
S	1	insufficient data[1]			
S	2	-1.36	0.42	2.0-10	8

[1] Only two trays had positive mean ΔM, precluding analysis of log. slope; only trays with positive mean ΔM are included in this analysis.

by his assumption of dry-centre moisture distribution.

5. The simple 60% proportion of total rainfall effect suggested by Van Wagner as a tentative adjustment for first-year slash was derived from a study of first-year Douglas-fir and western red cedar slash in coastal British Columbia (Lawson 1985). Van Wagner obtained a slightly better fit and R^2 (0.75 vs 0.70) for predicted vs. observed fuel moisture for this data set of 1 to 3 cm mixed species slash using 60% of the rainfall effect (Fig. 2). It should be noted that the coastal B.C. data was for the first season only, and began in late July, after the winter-logged slash had already cured below fibre saturation.

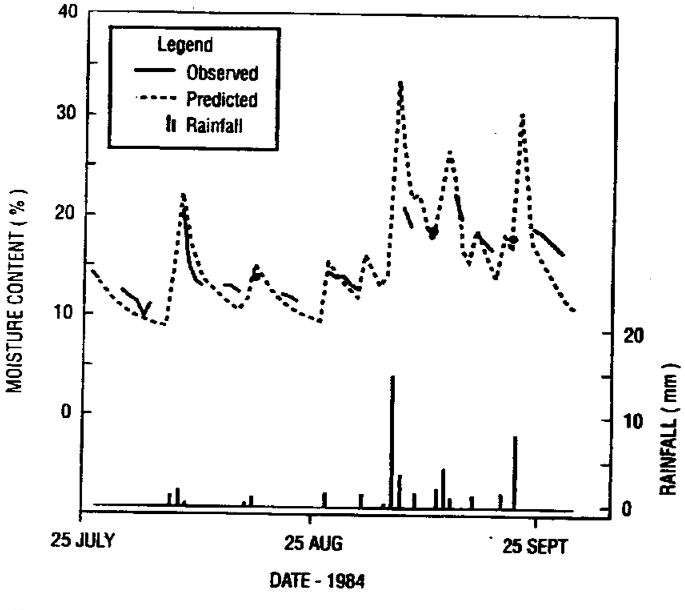

FIG 2. Predicted (Van Wagner (1987) model) compared to observed moisture content of first-year 1-3 cm Douglas-fir/western red cedar slash in trays near Shawnigan Lake, B.C., with rainfall amount.

Testing the proposed age adjustment in the present study was complicated by the "green" stage of first-year slash so a subset of the first-year data was evaluated, beginning July 10, 1987 after three consecutive days of heavy rains totalling 65 mm. Slash moistures had dropped to fibre saturation within a day or two of these rains, suggesting that a more realistic evaluation of the age adjustment than provided by the whole season might be possible using the second half-season data only. However, having determined that the model rainfall effect was too large for both ages and all diameters tested, we could not extend correlation analysis for the first-year slash because of insufficient data in that year's cured period. The second-year rainfall effect, a proposed 20% reduction from the third-year model standard value, was too large for the 2 to 5 cm diameters used in the basic model and much too large for the 6 and 10 cm sizes. Therefore, we decided to re-evaluate the rainfall effect independently of slash age, in combination with diameter, as discussed later with our other proposed model changes.

6. Our results agreed with Van Wagner (1987) with regard to the superiority of FFMC for predicting moisture content of very fine slash. Subalpine fir slash 0.1 to 1.0 cm was significantly correlated with FFMC in both years (R^2 = 0.69 and 0.87, respectively) whereas the slash model was not. However, the slash model performed better than FFMC for the 1.1 to 2.0 cm slash in both years, with a highly significant R^2 of 0.76 for the second year, as against 0.67 for FFMC.

Fuel moisture sticks were about as well correlated with fine slash moisture (0.1 to 1.0 cm) as FFMC for both years for all days (R^2 = 0.81 vs 0.69 and 0.82 vs. 0.87 for first-year and second-year respectively). However, for the more critical drier days, FFMC above 79, FFMC performed slightly better than fuel moisture sticks (R^2 = 0.87 vs 0.68).

These results, coupled with the good correlation between the slash model and the coastal B.C. first-year (cured) slash of 1 to 3 cm suggests that Van Wagner's explanation is probably correct, that as size decreases below 2 cm, the slash spends more time near its EMC and, also, its internal moisture distribution becomes more uniform. The problem, then, is to calibrate the various features of the model, i.e., EMC, effect of diameter on drying and wetting, and overall magnitude of the rainfall effect to produce more useful results over the range of diameters up to 10 cm.

The above results from testing the assumptions in the Van Wagner model suggested several changes to the model that could improve its applicability to our study's data (Fig. 3). Four changes were tried as follows:

1. Raising EMC from 5 to 9%, to better reflect observed ranges of minimum moistures of cured medium-sized slash from destructive sampling and tray measurements. The wax-sealed ends of the tray-sample pieces and the generally sound bark during the first

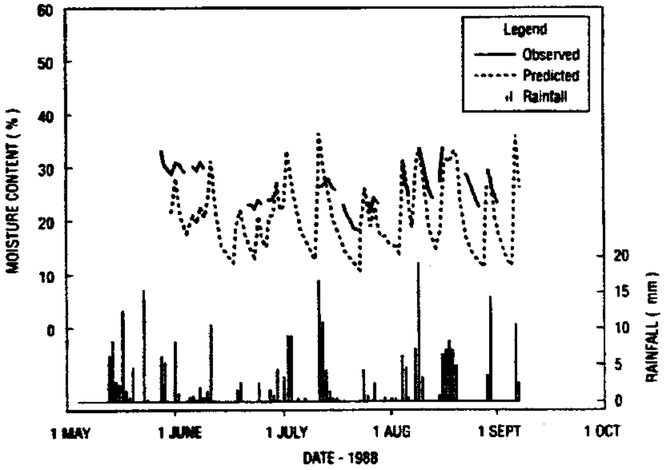

FIG 3. Predicted (Van Wagner (1987) model) compared to observed moisture content of second-year 4 cm white spruce slash in trays at Stony Lake, B.C. with rainfall amount.

two years appear to keep the EMC's for this material higher than for the original model data set, where ends were not sealed and pronounced cracking of bark had occurred. Van Wagner set the model EMC to 5% for mathematical reasons to ensure a spread of about 4 or 5% remained between EMC and expected field minimum values so that the model would function properly at the dry end (Van Wagner, personal communications, Apr. 6, 1989). Our increase to 9% would retain a similar spread for all but the finest slash sizes.

2. Reducing the rainfall effect with rain amount. A function of the same shape but half the magnitude was selected, following the pattern of the relationships with several of the size classes. Van Wagner's rain function f(R) approaches 1 at rainfall amount R of 30 mm, with larger rains having no further effect on cM and a maximum possible cM by his equation 3 of 57 points when EMC=5. Our reduction of the rainfall effect operates through reducing the f(R) to approach 1 at R of 15 mm, requiring the constant of 45.7 to be reduced to 23.7. This change results in a maximum possible cM of 15 points at our new EMC of 9.

3. Steepening the decline of rainfall effect with increasing diameter, to better reflect the negative slope of this relationship in our data. Van Wagner's slope of -0.5 was increased to -1.2 for trial.

4. Steepening the decline of drying rate with increasing diameter to better reflect the larger negative slope in our data. Van Wagner's square root relationship was increased from 0.5 to the 0.8 power.

Results of these model changes are summarized in Table 5. Overall, the changes significantly improved the R^2 and root mean square errors in regressions of predicted vs. observed fuel moistures for both ages for the 6 and 10 cm diameters, while not adversely affecting the 2.5 to 5 cm standard model size range. However, slopes continued to differ significantly from one, and as shown in Fig. 4, underprediction of the model increased for the standard diameters. No age effect could be resolved between first and second-year slash from the present analysis.

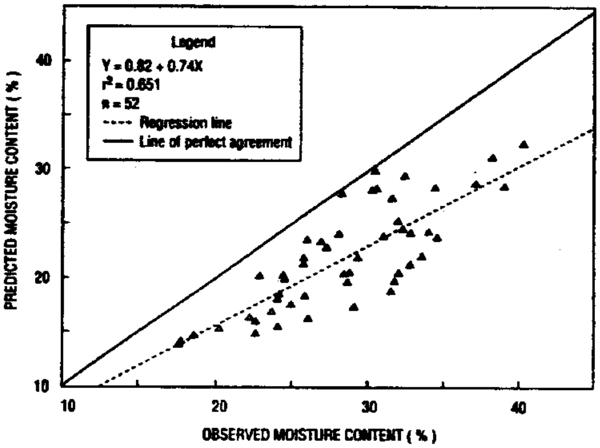

FIG 4. Regression of predicted (modified Van Wagner (1987) model) vs. observed moisture content of second-year 2.5 - 5.0 cm white spruce slash in trays at Stony Lake, B.C. compared to the line of perfect agreement.

It was interesting to compare the best possible correlations between the slash model predictions and daily moisture content of 2.5 to 5 cm slash in trays with correlations between FFMC and DMC, non-roundwood models in the FWI System. R^2 of 0.65 for the former compared with 0.70 from the latter multiple regression, with the same error of 3.0, quite similar to Simard et al.'s (1984) earlier results.

It would appear at this stage that the Van Wagner medium slash model is not as robust, i.e., extendible to slash fuel conditions beyond the data used in its derivation, as the standard fuel moisture codes of the FWI System. Further development and testing of medium slash moisture models using more refined data sets, in terms of the separation of "gross" rainfall effects from "net" combined wetting and subsequent drying, may be warranted. An appropriate age relationship from fresh "green" slash through total bark shedding age remains a need.

Direct measurement of woody fuel moisture can be an attractive option to weather-dependent mathematical models. In this study, the destructive samples taken approximately weekly for the "dry-centre" assumption tests were found to be highly correlated (R^2 = 0.70) between their oven-dry moisture contents and the mean of three separate readings of each piece taken with the Triton-2000 digital wood moisture meter. This regression was restricted to actual fuel moistures below 45%, and it is evident from the scatter plot (Fig. 5) that, as with most studies of these types of meters,

Table 5[1]

Linear regression statistics of outputs from slash model, modified for EMC, rainfall effect with rain amount, and for drying rates and rainfall effect with diameter.

Model feature	Species	Diam. (cm)	First-year slash					Second-year slash				
			Days (n)	Y-intercept	Slope	R^2	RMSE	Days (n)	Y-intercept	Slope	R^2	RMSE
xM	B	0.1-1				NS		-			NS	
	B	1.1-2	52	8.0	0.46	0.36*	4.1	52	4.0	0.53	0.70*	2.9
	S	2	52	14	0.28	0.20	5.1	52	1.0	0.45	0.48*	4.1
	B	2	52	8.3	0.51	0.25	5.0	52	1.2	0.43	0.58*	3.7
	S	2.5-5				NS		52	0.82	0.74	0.65*	2.9
	B	2.5-5				NS		52	-4.8	0.85	0.53*	3.4
	S	4				ND		52	0.0	0.85	0.57*	2.9
	B	4				ND		52	0.88	0.65	0.57*	3.0
	S	6	52	18	0.14	0.14	3.9	52	2.1	0.78	0.60*	2.3
	B	6				NS		51	-14	1.03	0.55*	2.6
	S	10	52	12	0.35	0.33*	2.9	51	8.1	0.60	.46*	2.0
	B	10	52	12	0.32	0.28*	3.1	51	12	0.33	.21	3.3
xk	B	0.1-1				NS					NS	
	B	1.1-2	24	0.05	0.60	0.26	0.04	21	0.04	0.46	0.47	0.04
	S	2				NS					NS	
	B	2				NS					NS	
	S	2.5-5				NS		13	0.04	0.39	0.31	0.03
	B	2.5-5				NS		21	0.04	0.70	0.36	0.03
	S	4				NS		21	0.03	0.53	0.40	0.02
	B	4				NS		21	0.03	0.44	0.41	0.02
	S	6				NS		21	0.03	0.38	0.48	0.01
	B	6				NS		19	0.03	0.68	0.46	0.01
	S	10				NS		21	0.03	0.30	0.46	0.01
	B	10				NS					NS	
cM	B	0.1-1				NS					NS	
	B	1.1-2				NS					NS	
	S	2	13	11	1.9	.41	9.2	19	9.7	1.1	0.49	5.7
	B	2				NS		19	9.0	1.1	0.67*	4.7
	S	2.5-5				NS		19	5.2	0.85	0.42	3.3
	B	2.5-5				NS					NS	
	S	4				ND					NS	
	B	4				ND					NS	
	S	6				NS					NS	
	B	6				NS					NS	
	S	10				NS					NS	
	B	10				NS					NS	

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[1] See Table 1 for explanatory notes

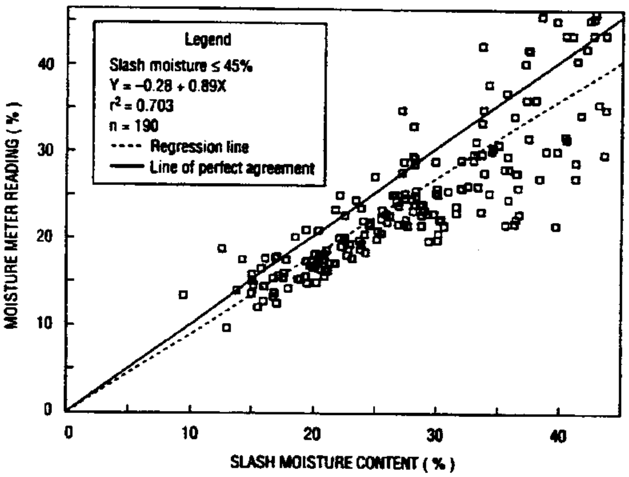

FIG 5. Regression of Triton-2000 moisture meter readings vs. observed 6 and 10 cm white spruce and subalpine fir moisture content compared to the line of perfect agreement.

their accuracy and precision falls off rapidly above fibre saturation, about 30%.

Conclusions

The Van Wagner (1987) medium slash model is highly correlated with the moisture content of white spruce and subalpine fir second-year slash up to 6 cm in diameter. The model is not well correlated with first-year slash moisture or with moisture content of slash as large as 10 cm diameter. This is because, even though the model's rainfall effect is reduced for new and second-year slash and slash of diameters greater than 4 cm, these reductions do not appear to be sufficient. The model ranges considerably above and below observed moisture contents of first- and second-year slash, the low end problem contributed to by a rather low and fixed EMC chosen for the model. Also, the model's "dry-centre" assumption about internal moisture distribution, was not verified consistently for slash larger than 3 cm, resulting in predicted daily drying rates too high for diameters larger than the 4 cm standard. The present analysis of drying rate as affected by current weather was not conclusive, but suggests the possibility of a stronger relationship to temperature than in the model.

Moisture of slash less than 1 cm in diameter is better predicted by FFMC or fuel moisture sticks than the medium slash model, and even medium sized slash (2.5 to 5 cm) is highly correlated with FFMC and DMC. Moisture meters can be used effectively and accurately below 30% to directly measure moisture content of medium-sized slash; however, as with any fuel sampling scheme, obtaining readings representative of the fuel of interest over the cutover area is a problem.

Further study of moisture model improvements for medium-sized slash are probably warranted, as the present model and test procedures and results all have shortcomings. Future work should include the evaluation of potential improvements in prediction of slash fuel consumption using models or measurements of medium-sized slash moisture for prescribed fire decision-aids, before major new work on slash moisture models for the CFFDRS is undertaken. Correlative models using standard moisture codes from the FWI System may be difficult to significantly improve on when prescribed fire behavior and impact prediction is the ultimate fire management objective.

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Endnotes

[1] Referred to as fuel moisture sticks in rest of paper. B.C. Forest Service half-inch (1.3 cm) Douglas-fir fuel moisture sticks weighing 100 g oven-dry are currently manufactured to B.C.F.S. standards (Bell 1970) by Dick's Firesticks, Mackenzie, B.C. under the trade name "The Dick Fuel Moisture Stick".

[2] Throughout this paper cM denotes predicted net moisture content change after rainfall plus subsequent drying; ΔM denotes the observed value. Final moisture content predicted for the day is denoted xM, while M denotes the observed value.

[3] Triton moisture meters are manufactured by Valley Products and Design Inc., Milford, Pa.

[4] "highly significant" in this paper denotes significance level of 0.0001.

[5] Defined here as the innermost 1 or 2 cm strata having lower moisture content than the rest of the piece.

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