A Moisture Content Model for Medium-Sized Logging Slash

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1. INTRODUCTION

The Canadian Forest Fire Weather Index System (FWI System) contains models for following, from day to day, the moisture contents of three classes of forest fuels with different timelags. These classes are all forest floor components of varying weight and thickness, as befits a fire danger rating that applies primarily to the forest (Van Wagner 1987). In contrast, measurement of fire danger and behavior in forest cutovers requires one or more moisture models for the woody components of logging slash. It was to fill this need that the present slash moisture model was developed. Currently, any Canadian predictions of fire behavior in slash are made with the help of the forest floor models.

The reference most pertinent to the present work is by Simard et al. (1984), who reported a study of moisture content and its daily variation in jack pine slash in comparison with available American and Canadian fuel moisture models. Fair correlation was obtained between certain models and some sizes and conditions of slash wood, but no model performed well in both correlation and absolute prediction. Furthermore, the best prediction equations contained pairs of models of different timelags. It should be possible to do better with a model specifically designed for slash.

The size of wood chosen as the basis of the model is 4 cm in diameter, partly because a satisfactory data-set for such material was available, and partly because its diameter was judged to be near the upper limit of the range of sizes that affect the rates of spread and frontal intensity. It was hoped that a moisture model for such a size would help in estimating both rate of spread and fuel consumption in slash fires, whether wild or prescribed.

The purpose of the model was to estimate, from day to day, the moisture content of the 4-cm slash using the standard daily weather observations as inputs. In concept, it is a moisture budget that gains moisture from rain and loses moisture every day according to the weather. The model thus consists of two phases, a rainfall phase and a drying phase, each of which required analysis according to the pertinent independent variables.

The following sections of the paper include descriptions of the data-set, an account of the model's development, results of tests of its ability to estimate moisture content, and a discussion of how it might be generalized for a range of slash wood ages and sizes.

2. MODEL DEVELOPMENT

2.1 <u>The Data-Set</u>

Of several slash studies available in Canadian Forestry Service records, the most appropriate was that reported by B.J. Stocks and J.D. Walker of the Great Lakes Forestry Centre (Stocks and Walker 1972). Complete data were kindly supplied by B.J. Stocks.

The study was carried out in 1970 and 1971, but only in 1971 were the observations complete enough for the present purpose. The pre-logging forest was primarily 80-year-old, jack pine, with a minor component of black spruce. The slash load varied from 35 to 118 t/ac, with an average of 60 t/ac. The slash was in its third summer after logging, and some of the needles were already down.

Fifteen experimental fires on square plots measuring 0.4 ha in area were burned under a wide range of conditions, with complete records of spread rate and fuel consumption, thus providing the means of testing performance of the slash moisture model for predicting fire behavior. Such performance tests are, however, not part of the present study.

Samples of several sizes of material were set in trays in the slash and weighed every afternoon for 95 consecutive days. The largest size sampled was the 1- to 2-inch class; this range equals 2.54 to 5.08 cm, with a midpoint of 3.81, or about 4 cm in diameter. The standard fire weather observations of temperature, relative humidity, wind speed, and 24-hr rain were taken daily at noon, standard time. At the end of the run, the material was oven-dried and the daily moisture contents calculated.

Destructive samples of all materials were taken daily, as well as the tray measurements. These data were checked for possible usefulness, but found too erratic from day-to- day for worthwhile analysis. Their general trend, however, ran about the same level as the tray samples, indicating that there was no appreciable bias in either method.

Weather during the study run was highly variable, including periods of up to 10 days without rain, and periods of several days in a row with substantial rainfall. Ranges for the noon observations were: for temperature, 10 to 30°C; for relative humidity, 17 to 100%; and for wind speed, 4 to 45 km/h. The highest rainfall was 27.9 mm. Observed afternoon moisture content of the slash in question ranged from 9.6 to 42.6%.

2.2 Development of the Drying Phase

As with the standard fuel moisture models of the FWI system (Van Wagner 1987), a negative exponential drying process was assumed, of the form

$$(M-E)/(M_0-E) = e^{-kt} \qquad (1)$$

where M is final moisture content (%),
M_0 is initial moisture content,
E is equilibrium moisture content (EMC),
t is time, and
k is logarithmic drying rate.

Time being measured in days, t becomes 1. The EMC certainly varies with weather conditions, but this refinement was judged unnecessary for material as slow drying as 4-cm wood. The EMC was therefore set constant at 5%, a level deemed appropriate after some trial for such well- exposed fuel. Use of a constant EMC produces some inevitable distortion in the calculation of k on muggy days when the true EMC is undoubtedly higher than 5%. This was considered a fair price to pay for the resulting convenience. The key to the drying phase is therefore the estimation of k; this was carried out in terms of logarithm to base 10.

Of the 95 days in the run, 60 were rainless; k was calculated for each by Eqn. 1, entering yesterday's M for M_0. The next step was the individual regression of k against temperature (T), relative humidity (H), and wind speed (W), in that order. In each case, the degree of correlation was negligible, in spite of the substantial ranges of each weather variable. Even a joint regression of k against all three produced an R^2 of only 0.05. And yet the individual k's varied from near zero to 0.394, an average of about 0.0935/day. Clearly some other factor was at work.

Since k was always highest just after a rainfall, the obvious choice was the initial moisture content, M_0. Regression of k against M_0 alone yielded an R^2 of 0.63, with an apparent linear pattern. This effect was contrary to all experience with the analysis of forest-floor drying patterns for the FWI System; for example, laboratory experiments produced no variation in k when pine litter was dried under identical conditions of T and H over a wide range of M_0 (Van Wagner 1981). The logical explanation is that wood pieces absorb rain mainly in their outer rings, and later lose it by evaporation more readily than if were distributed evenly throughout the piece. The greater the rain effect, the faster the apparent subsequent drying rate; furthermore, at no time did these pieces approach saturation, even after several days heavy rain. This argument is the same one used by Fosberg (1971) in his design of the 100-hr timelag fuel model for the American National Fire-Danger Rating system. In that model, the theoretical timelag for wood of the given size was reduced to account for the faster drying rate that results from favorable internal distribution of moisture after rain. The argument is presented in more detail by Fosberg (1972).

Rather than adopt a completely empirical additive correlation model for k, a compound semi-theoretical form was chosen, based on functions for each of T, H, W, and M_0. The forms of the functions of T, H, and W were drawn in part from the corresponding functions in the Fine Fuel Moisture Code (FFMC) of the FWI System (Van Wagner 1987). However, their strengths were adjusted in accord with the regression results. The form of $f(M_0)$ is a gentle power function of (M_0-E), where E = 5. Each function has an assumed individual coefficient, which all blend into one when the four functions are multiplied together. This general coefficient was set by trial. The whole equation for k is, then

$$k = 0.023\, e^{0.0182T}[1-(H/100)^{1.7}]\,(0.1 + 0.0151W^{0.5})(M_0-5)^{1.2} \qquad (2)$$

When the 60 calculated values were regressed against the corresponding actual values, an R^2 of 0.67 resulted, identical to that obtained from the additive four-variable linear regression. Because the chosen model pays specific attention to the physics of the process, it was deemed a satisfactory and adequate result. The relative influence on k of the four variables over reasonable ranges of each is tabulated below.

Variable	Range	Proportional effect on k
T	10-40°C	1:1.73
H	20-80%	2.96:1
W	5-40 km/h	1:1.46
M_0	10-40%	1:10.3

Humidity has a relatively stronger effect than in the FFMC, reflecting the extra effect of solar heating under clear skies at low humidity; however, the dominant effect of M_0 in comparison with weather variables is obvious.

2.3 Development of the Rainfall Phase

Of the 95 days in the run, 35 registered some rain, ranging from 0.3 to 27.9 mm, each of which caused some immediate rise in moisture content. The key to the rainfall phase is thus the estimation of this rise, namely ΔM. However, each rain-day's moisture content as measured in such a field study is the result not only of the ΔM due to rain, but also of any drying that took place after the rain stopped. (Rain was always measured at time of weighing, to avoid confusing two 24-hr periods.) The main problem was, therefore, interpretation of these "net" ΔMs (some negative) to yield the true "gross" ΔMs required by the model. The analysis was carried out in terms of two independent variables, R and M_0, with opposing effects; in other words, ΔM was assumed to increase with increasing R, but to decrease with increasing M_0.

The 35 net ΔMs were plotted separately against R (Fig. 1) and M_0 (Fig. 2). Distribution of the points in each was deemed to be affected not only by interaction with the other variable, but also by the unknown amount of drying after each rain. Small rains thus usually yielded negative values. The shape of the functions of R and M_0 was therefore interpreted from the upper edge of each distribution. Thus, at each value of R, the highest ΔMs were judged the result of low M_0 and little or no drying after rain; the graphed function f(R) in Fig. 1 was therefore applied, a curve rising sharply from zero at zero R, but levelling off at high R. Similarly, at each value of M_0, the highest ΔMs were judged the result of high R and little or no drying after rain; the graphed function $f(M_0)$ in Fig. 2 has a finite high value at zero M_0, falling to zero at $M_0 = 50$.

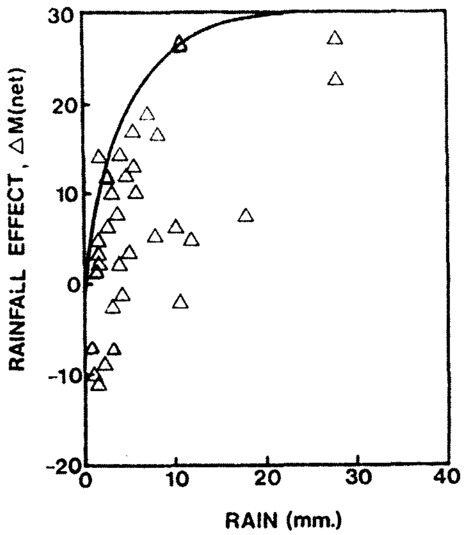


Figure 1. Graph of rainfall effect Δm (net) over rain amount R, plus curve of f(R).

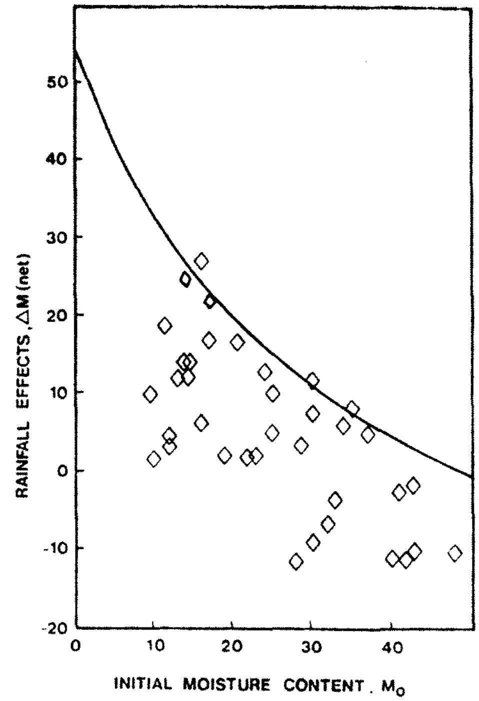


Figure 2. Graph of rainfall effect Δm (net) over initial moisture content M_0, plus curve of $f(M_0)$.

After these two functions were multiplied together, the required general coefficient was determined by trial. The equation adopted for ΔM (the gross rise) is

$$\Delta M = 45.7(1-e^{-0.22R})(50-M_0)/(30.8 + M_0) \quad \ldots \quad (3)$$

This equation could only be tested in combination with the drying phase in terms of net ΔM. A regression of calculated net ΔM vs. actual net ΔM yielded an R-square of 0.78, which was judged satisfactory. No simple multiple regression procedure in direct terms of R and M_0 could be devised to match the physical process leading to net ΔM after both rain and subsequent drying.

In Eqn. 3, the rain function f(R) approaches 1 at about R = 30 mm; greater rains therefore have no further effect on ΔM. The greatest possible ΔM by Eqn. 3 is 57 points, only possible when M_0 = 5% (the EMC). The equation has one limitation, that M_0 not exceed 50; otherwise negative values of ΔM would result.

3. MODEL STRUCTURE AND TESTS

With the forms of both phases in hand, the model could now be put together. In case of rain, ΔM is added to M_0 to yield M_r, the moisture content immediately after rain:

$$M_r = M_0 + \Delta M \quad (4)$$

because the rain function f(R) in Eqn. 3 equals zero at zero rain, Eqn. 3 can be used every day for convenience, and M_0 in Eqn. 2, the formula for k, can be replaced with M_r. The final M for the day is then computed from a form of Eqn. 1, in which k is based on logs to base 10, E = 5, and M_0 becomes M_r:

$$M = 10^{-k} (M_r - 5) + 5 \qquad (5)$$

Because of the limitation in the equation for ΔM, if M does not dry below 50, it must be set at 50.

The procedure in point form is thus as follows:

1) Specify a starting M_0.
2) Compute ΔM from R and M_0 by Eqn. 3.
3) Compute M_r from M_0 and ΔM by Eqn. 4.
4) Compute k from T, H, W, and M_r by Eqn. 2.
5) If $k < 0$, let $k = 0$.
6) Compute M from k and M_r by Eqn. 5.
7) If $M > 50$, let $M = 50$.
8) Repeat daily, each day's M becoming the next day's M_0.

The first step in verifying the model was to test its output against the data-set on which it is based. This was done by regressing the calculated values against the actual values of the three basic features of the model, namely 1) the net value of ΔM following rain plus subsequent drying, 2) the logarithmic drying rate k, and 3) the final moisture content M for the day. The properties of these regressions, in terms of their linear coefficients and the proportion of variance explained, are listed in Table 1.

Table 1.

Linear regressions of the model's output against the data-set on which it is based.

Model feature	Days	Y-intercept[1]	Slope[2]	R-square[3]
Net ΔM after rain	35	-1.5	1.08	0.78
Log. drying rate k	60	0.032	0.65	0.67
Moisture content M	95	2.63	0.85	0.82

[1] All marginal in significance of difference from zero.
[2] All differences from one highly significant.
[3] All highly significant.

Although the slopes in Table 1 all differ significantly from one in the statistical sense, the differences are not judged serious in the practical sense. These weaknesses result from the choice of a compound semi-theoretical model for k rather than a purely empirical regression model, plus the difficulty of accounting for subsequent drying in the rain-effect analysis. More trials to adjust the various coefficients might result in improvement, but the R-squares in Table 1 were deemed satisfactory for the present.

The best single picture of the model's performance against its own data-set is a graph of the day-to-day moisture contents over time, the calculated values shown along with the actual ones, as seen in Fig. 3. The generally good match demonstrates that the original data-set was internally consistent and therefore amenable to satisfactory analysis.

Unfortunately, no other slash moisture data-sets are available within the Canadian Forestry Service records that provide the day-to-day continuity and consistency needed for impartial external testing. As alternatives to the model itself, the woody fuel moisture models of the American National Fire-Danger Rating System (Bradshaw and Deeming 1983) were considered for trial; however, records of rain duration, a necessary input, were lacking.

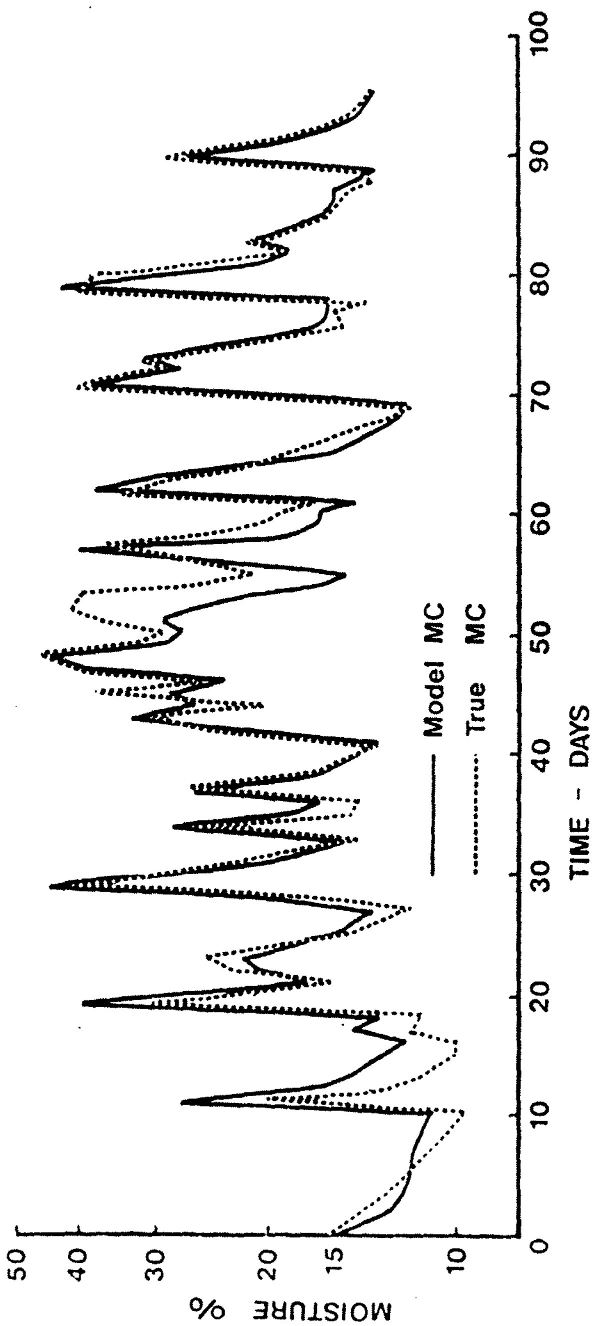
What about the model's timelag? This is simply $1/(k \ln 10)$ and will vary from day to day not only with the weather, but with M_0 as well. The standard conditions for comparison of timelag within the FWI System are $T = 21.1°C$, $H = 45\%$, and $W = 12$ km/h. Then, when M_0 is 20% (the average during the experimental run), $k = 0.0985$, and the timelag is thus 4.4 days. As in the FWI System, "one day" means one 24-hr period with its normal cycle of T and H, not 24 hr of continuous drying. Such a timelag is intermediate between those of the Fine Fuel Moisture Code (2/3 day), and the Duff Moisture Code (12 days). Otherwise, the two essential points on which this 4-cm slash moisture model differs from the forest floor models of the FWI System are that 1) the effect of rain is much weaker, and 2) the daily timelag varies with the initial moisture content as well as with the weather.

4. EFFECTS OF AGE AND DIAMETER

The present model was derived from slash exposures of a particular species, age, and size. Setting aside as secondary the problem of species differences, the other main concerns are the variations in moisture fluctuation due to slash age and diameter.

With respect to age, the main physical effect is cracking and peeling of the bark. The result is that rain water is trapped and absorbed more readily as each summer passes. Simard et al. (1984), it is true, show no difference between "bark" and "no-bark" with respect to moisture content after rain (see their Fig. 2). Their "bark" samples were, however, already in their second summer; it is rather the contrast between fresh slash (with its tight, intact bark) and older slash that is in question here.

Figure 3. Graph of moisture content over time, actual trend compared with model output.



A tentative adjustment for age can be derived from data on a West Coast slash study kindly supplied by B.D. Lawson of the Canadian Forestry Service, Pacific Forestry Centre. The data-set consists of 38 days on which the same material was weighed each day. Although the species were different, and the slash pieces were 3 cm rather than 4 cm in diameter, the model values yielded a reasonable R^2 of 0.70 when regressed against the observed moisture contents. The model overpredicted, however, presumably because the slash was in its first summer only, with bark nearly intact, whereas the model is based on third-year slash. Reducing the gross values of ΔM on the rain days to 60% of the model values produced a better fit and a slightly improved R^2 of 0.75 as well. This ratio of ΔMs was then used to design a simple age effect.

The constant 45.7 in Equation 3 controls the simple magnitude of the increase due to rain (ΔM). If that value represents slash in its third summer, then 60% of it, or 27.4, should be appropriate for first-summer slash, and an intermediate value, 36.6, for the second summer. Ultimately, when enough data are available to define it, a rising function that levels off at some maximum value when all bark has fallen should take the place of this temporary three- level constant. Meanwhile this tentative adjustment is available for trial.

With respect to slash size, there are two possible ways of extending a moisture model developed for one size, to apply it to a range of sizes. One, suitable only for larger sizes, is to base today's large-size moisture content on some fraction of yesterday's large-size value plus one-minus-that-fraction of today's small- size value. Such a damping scheme was used by Furman (1975) for predicting the daily moisture content of 3.8-cm sticks from that of 1.3-cm sticks. Another way is to design size-dependent functions for the separate drying and wetting phases of the model; this is the approach chosen here.

As size increases, any unevenness in the distribution of moisture along the radius becomes more and more important. Suppose that slash wood of appreciable size varies in moisture content in one of two ways, the "dry-centre mode" or the "wet-centre mode". In the former, the centre is generally drier than the outer annuli; moisture is absorbed and lost mainly from these outer layers, and the apparent drying rate for the piece as a whole would be faster than expected for uniform moisture distribution. In the latter mode, the centre is generally wetter than the outer annuli; moisture is again gained and lost mainly in the outer layers, but the apparent drying rate would be much slower than for the dry-centre mode.

Because the maximum moisture content observed in the 4-cm slash pieces never approached the known level of wood saturation, it is obvious that this material behaved according to the dry-centre mode. Simard's (1984) data also exhibited relatively low after-rain moisture content's for diameters up to 10 cm (his Fig. 1); it is therefore assumed that slash wood in the field, up to that size at least, behaves in general by the dry-centre mode. Three sets of field observations on the variation of drying rates with size support this assumption. Stocks and Walker (1972) provide one set of average drying rates for sizes from 0.3 to 4 cm. Péch (1969) and Simard et al. (1984), by analysis of their graphed drying patterns, provide two others. The three sets are graphed together on log coordinates in Fig. 4; a reasonable tentative conclusion is that k varies approximately with the square root of diameter. That is,

$$k/k_0 = (D_0/D)^{0.5} \qquad (7)$$

where k_0 and D_0 are values for the basic 4-cm model. Thus, since $D_0^{0.5} = 2$, the value of k for any other diameter D becomes

$$k = 2\ k_0/D^{0.5} \qquad (8)$$

In contrast, the variation of k with diameter when drying by the wet-centre mode is much stronger. For example, Nelson (1969) dried wooden rods from about 100% moisture content, and found that the timelag was related to the square of diameter (rather than the square root), as his theory predicted for this case. A similar diameter-squared relationship links the timelags of the American fuel moisture models (Bradshaw and Deeming 1983).

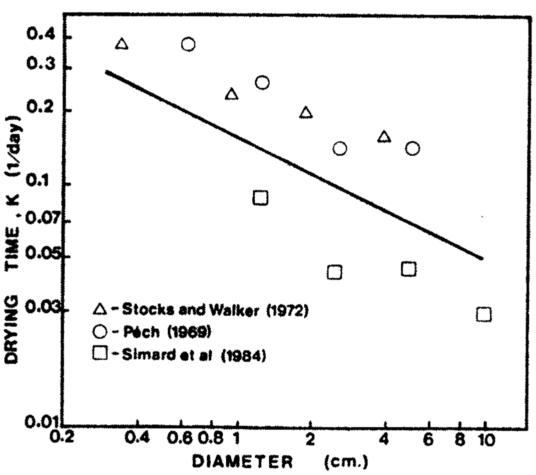


Figure 4. Variation of logarithmic drying rate k with piece diameter D from three sources. Only the slope of each set is relevant.

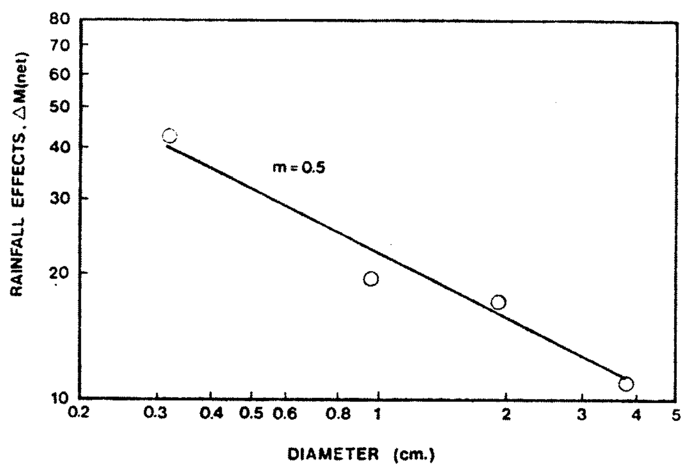


Figure 5. Variation of rainfall effect Δm (net) with piece diameter D from data of Stocks and Walker (1972). Only the slope of the data is relevant.

With respect to the rain effect, if moisture were distributed evenly throughout the piece as it was absorbed, the resulting moisture rise (ΔM) would be proportional to the piece's surface-to-volume ratio. This equals 2/r; ΔM should then vary inversely with radius or diameter. To test this concept, average net ΔMs for four size classes were compiled from the data of Stocks and Walker (1972), and are graphed in Fig. 5. The slope of the double-log line is -0.5 rather than -1, and the discrepancy with theory is again probably in some way due to non-uniform moisture distribution. The same square-root relationship of ΔM with diameter emerges, therefore, as for the drying rate

(Eqn. 8). That is, since $D_0^{0.5} = 2$ as before

$$\Delta M = 2(\Delta M)_0/D^{0.5} \qquad (9)$$

where ΔM and D are values for a given diameter, and $(\Delta M)_0$ the basic 4-cm value.

To apply the expanded model, the adjustment for slash age is applied, modifying the rain coefficient as described earlier. Then, to apply the model to slash of size other than 4 cm, k_0 and $(\Delta M)_0$ are computed by Eqns. 2 and 3 respectively, then further modified by Eqns. 8 and 9.

To test the effectiveness of the variable-diameter features of the model, correlations of its output for the four sizes of slash exposed by Stocks and Walker (1972) were run against the actual moisture data. Also, because the lower two diameters were small enough to fall within the range normally considered "fine fuel", correlations with the Fine Fuel Moisture Code (FFMC) were run as well. Table 2 lists these results simply in terms of R^2, the statistic deemed most suitable for this comparative purpose.

Table 2.

Values of R^2 for correlations of moisture content data of four slash sizes with a) the FFMC and b) the variable-diameter slash moisture model.

Slash diam. (cm)	R-square for correlations with FFMC	Slash model M
0.3	0.85	0.40
1.0	0.50	0.65
1.9	0.46	0.72
4.0	0.15	0.82

Two points are worth noting in these results. One is the obvious superiority of the FFMC for monitoring very fine material. The other is the steadily poorer performance of the slash model as diameter decreased, even though the diameter effect was supposedly compensated. The likely explanation is that, as size decreases, the material spends more and more time near its EMC,and, also, the internal moisture distribution becomes more uniform. The FFMC, with variable EMC and k that remains constant with M, is then bound to do better than the slash model. These data suggest that the slash model with its M-dependent k becomes preferable to the FFMC as diameter rises above about 2 cm.

5. CONCLUSION

The form of a potential general slash moisture model is now complete. The basic 4-cm model is on moderately firm ground, but the extensions to account for slash age and size are obviously tentative. A good deal of testing by comparison with field exposures is required, and further modifications can be expected. In any event, these additional features could apply only to slash behaving according to the dry- centre mode, and for a limited size range from about 2 to 10 cm. Very large logs may vary in moisture content in a complex manner depending on which mode, dry-centre or wet-centre, they tend to follow. Furthermore, as diameter increases, interest in the integrated moisture content of the whole piece decreases, and the state of the outer annuli becomes the primary concern.

6. ACKNOWLEDGMENTS

This work was possible only through the cooperation of B.J. Stocks and J.D. Walker, who supplied data from study files at the Great Lakes Forestry Centre, and B.D. Lawson of the Pacific Forestry Centre, who provided an unpublished data-set of slash exposures on the West Coast.

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