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Moisture Content Calculations for 1000-Hour Timelag Fuels

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ABSTRACT. Techniques to calculate 1000-hour timelag fuel moistures were developed from theory of water movement in wood. The 1000-hour timelag fuel moisture is computed from mean daily temperatures and humidities and precipitation duration. Comparison of calculated and observed fuel moistures showed good agreement. Techniques to determine the seasonal starting value of the 1000-hour timelag fuel moisture are based on monthly climatological summaries. The seasonal starting value calculation was made from a least squares regression equation. FOREST SCI. 27:19–26.

ADDITIONAL KEY WORDS. Forest fuels, forest fire hazard, forest fuel moisture, climatology.

FIRE RESEARCHERS became aware early that fuels of different sizes responded differently to weather and that fire behavior and damage were markedly affected by the moisture content of these different fuels. Gisborne (1928, 1933) introduced two size classes of aerial fuels (½-inch-diam and 2-inch-diam dowels) and a measure of duff moisture. Shortly after this initial study, he began to characterize seasonal variations in fire danger, utilizing 6-, 12-, and 18-inch-diam logs (Brackebusch 1975). These fuel sizes were later adopted as the basis for fuel classifications of the National Fire Danger Rating System (Deeming and others 1977) wherein ½-inch-diam sticks correspond approximately to the 10-hour timelag, 2-inch-diam wood dowels correspond to the 100-hour timelag, and 6-inch-diam logs correspond to the 1000-hour timelag.

This discussion of techniques for evaluating 1000-hour timelag fuel moisture is significant because current management practices require both forecast and current fuel moisture data for fire danger and behavior assessment (Albini 1976, Rothermel 1972) and because measurement of fuel moisture in large fuels is difficult. Moreover, these methods are the basis for calculations used by the National Fire Danger Rating System. Techniques are also presented which determine the seasonal starting value of the 1000-hour timelag fuel moisture as an alternative to extended operation of fire weather stations.

THEORY OF THE COMPUTATIONAL SYSTEM

The basic equation for fuel moisture changes (Fosberg 1972) is

$$\frac{\delta m}{\Delta m} = \frac{m - m_0}{m_b - m_0} = 1 - \zeta \exp(-\delta t/\tau) \tag{1}$$

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where δm is the actual moisture change (the difference between the final moisture, m, and the starting moisture, m_0) over the time interval δt; Δm is the potential moisture change (the difference between the environmental boundary condition, m_b, and the starting moisture content); and τ is the timelag constant of the fuel. The environmental coefficient, ζ, accounts for the changes in moisture due to nonuniform moisture distribution inside the fuel, and for environmental temperature, humidity, and precipitation variations. The timelag is related to the fuel diameter and the internal moisture diffusivity through the Fourier number (Fosberg 1973). The internal moisture diffusivity is species dependent (Stamm 1946, Fosberg 1970).

The time interval for an individual calculation strongly influences the procedures for defining the boundary condition, m_b. Since environmental temperature, humidity, and precipitation are continually changing, so the boundary condition should be expected to change continuously. Only rarely would environmental change occur which would produce a constant boundary condition. A traditional approach, the mean value theorem (Taylor 1955, p. 51–52), has been used effectively in reducing a time dependent factor to a single coefficient.

The time interval defining the boundary value must be less than one timelag and preferably should be a small fraction of that timelag. In the absence of precipitation, the boundary condition is defined in terms of the equilibrium moisture content. If precipitation or dew occur, large amounts of water are available to be absorbed by the fuel, and the boundary condition changes to a different set of functions (Fosberg 1972). If the precipitation occurs as snow, or if frost is present on the fuel, movement of water takes place in the vapor stage, and the boundary condition is based on a 100 percent relative humidity environment (McCammon 1976).

The boundary condition can be expressed in general terms:

$$m_b = \frac{(\delta t - P)\bar{m}_e + \delta_S\, 30\, P_S + \delta_R P_R (a P_R + b)}{\delta t} \tag{2}$$

where

δt = averaging time
P_R = duration of precipitation for rain
P_S = duration of precipitation for snow
$P = P_R + P_S$, the total precipitation duration
δ_S = Kroneker delta indicating occurrence of snow
δ_R = Kroneker delta indicating occurrence of rain.

This boundary condition is a time-weighted mean. The coefficients $a = 2.7$ percent/hour and $b = 76$ percent determine the rate of liquid uptake by the fuel and have been determined experimentally (Fosberg 1972). The coefficient 30 represents the mean fiber saturation point under snow (McCammon 1976). The integral mean equilibrium moisture content $\bar{m}_e$ is defined by

$$\bar{m}_e = \frac{1}{\delta t} \int_0^{\delta t} m_e \, dt$$

where $\bar{m}_e$ is the instantaneous equilibrium moisture defined by the instantaneous temperature and humidity (USDA Forest Service 1974, p. 3–8) which are calculated from the equations developed by Simard (1968). This is also a time-weighted function for which the solution must be approximated using existing data. Specific approximations are defined later. The equilibrium moisture content functions for temperature in degrees Fahrenheit, T, and relative humidity in percent, h, are

$$m_e = 0.03229 + 0.281073h - 0.000578hT, \text{ for } h \leqslant 10 \text{ percent} \quad (3a)$$

$$m_e = 2.22749 + 0.160107h - 0.014784T, \text{ for } 10\% < h \leqslant 50 \text{ percent} \quad (3b)$$

$$m_e = 21.0606 + 0.005565h^2 - 0.00035hT - 0.483199h, \text{ for } h > 50 \text{ percent.} \quad (3c)$$

Specific Calculations for the 1000-Hour Timelag Fuels

The coefficients in equations (1) and (2) must be defined in order to apply equations (1) and (2) to the 1000-hour timelag fuel. A long averaging period is used to calculate the boundary condition because of the minimal response of 1000-hour timelag fuel to diurnal changes. We have chosen a 7-day period to average the boundary condition. Here τ is defined as 1000 hours and δt as 24 hours per day times 7 days to equal 168 hours. Rearranging equation (1) and substituting the specific coefficients into equation (1), the specific moisture content equation for the 1000-hour timelag fuel becomes

$$^{1000}m = {}^{1000}m_0 + ({}^{1000}m_b - {}^{1000}m_0)(1 - 0.82 \exp(-168/1000)). \quad (4)$$

The notation in this equation is the same as in equation (1), except that the superscript now indicates the 1000-hour timelag fuel. The boundary condition for the 1000-hour timelag fuel is calculated from a 7-day average of the daily boundary conditions.

The value of ζ equal to 0.82 is based on the stable range of ζ defined by Fosberg (1972) for a 7-day calculation period for the 1000 hour timelag fuel. The coefficient ζ is always assumed to equal 1 in wood kiln drying. Under varying environmental conditions, given a ζ value of 1 and a constant timelag, the solution produces substantial error in fuel moisture calculation. Two techniques to resolve this problem have been proposed: The first, used in Canada, defines a variable timelag where ζ equals 1; the second approach, used here, allows ζ to vary and holds the timelag constant. The choice of ζ to account for environmental change is based on molecular changes in cellulose implied by a varying timelag (Fosberg 1973).

Both solutions contain a coefficient which cannot be defined from first principles. This solution is based on an analysis of the stable values of ζ and therefore defines the integration period of 7 to 10 days for a fuel with a timelag of 1000 hours (Fosberg 1972). Equations (4) and (5) represent the specific expansion and solution to equations (1), (2), and (3) for the 1000-hour timelag fuel.

The daily boundary value is

$$^{1000}m_{bi} = ((24 - P)(m_e[T_{\max}, h_{\min}] + m_e[T_{\min}, h_{\max}])/2 + \delta_S 30\, P_S + \delta_R P_R(2.7P_R + 76))/24 \quad (5)$$

where $m_e[T_{\max}, h_{\min}]$ is the equilibrium moisture based on maximum temperature ($T_{\max}$) and minimum relative humidity ($h_{\min}$) and $m_e[T_{\min}, h_{\max}]$ is the equilibrium moisture defined by minimum temperature and maximum humidity. This defined equilibrium moisture content is based on data limitations. P is the precipitation duration in hours. δ_S has a value of 1 if the precipitation is snow, otherwise the value is zero. Similarly, δ_R has a value of 1 if the precipitation is rain, otherwise the value is zero.

The 7-day average boundary condition is

$$^{1000}m_b = \frac{1}{7}\sum_{i=1}^{7} {}^{1000}m_{bi}. \quad (6)$$

Solution of equations (3), (4), (5), and (6) for the 1000-hour timelag fuel moisture are based on daily maximum and minimum temperatures and humidities and on the daily precipitation duration.

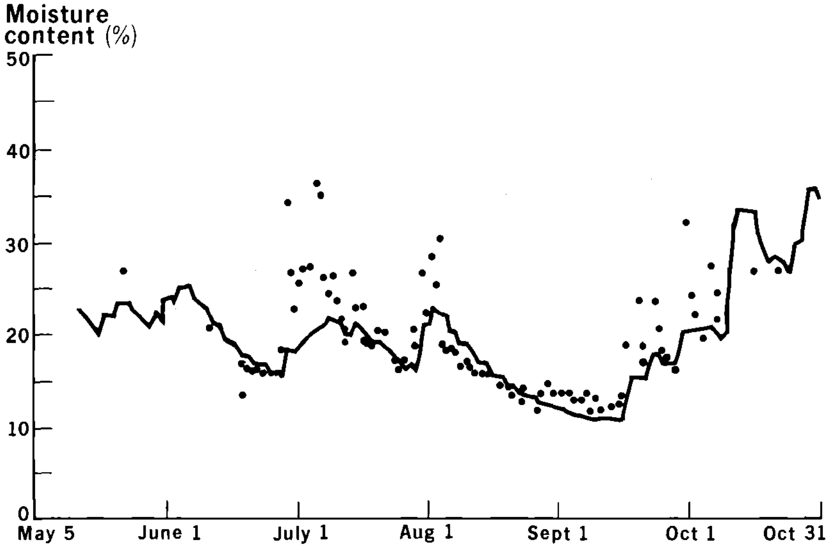

FIGURE 1. Comparison of predicted (line) and observed (points) 1000-hour timelag fuel moistures for 1955 at Priest River, Idaho.

CALCULATION OF THE STARTING VALUE FOR THE FIRE SEASON

Selecting the seasonal beginning value for buildup fuels and buildup indices has always posed a fire management problem. Potential fire behavior early in the season may be much different than that calculated if an erroneous value is chosen. Although the calculated moisture will converge to the correct value after a period of time, the 1000-hour moisture may be incorrect for as long as 2 months.

A model to determine the initial moisture content of 1000-hour timelag fuel was developed, using weather data from the Priest River Experimental Forest, Idaho—consisting of monthly mean temperature, relative humidity, and number of days with precipitation—in conjunction with data derived from 6-inch-diam logs in the large-log study (Brackebusch 1975). The general framework of the model is based on equations (1) and (2). A least squares fit procedure was used, since the monthly climatological data available to determine the starting value of the 1000-hour timelag fuel do not meet all the requirements of equations (1) and (2). The final equation is

$$ {}_{1000}m = \frac{(24D - 27.9P_D)\bar{m}_e + 762P_D}{24D} \qquad (7) $$

where D is the number of days in the preceding month, P_D is the number of days on which precipitation fell, and $\bar{m}_e$ is the mean equilibrium moisture content determined from the mean monthly temperature and relative humidity. These coefficients are for the month immediately preceding the fire season. Estimation of these coefficients was based on 40 months of data and gave a root mean square error of 4.4 percent moisture content.

RESULTS

Calculations of 1000-hour timelag fuel moisture were made in 1942, 1943, and 1950 to 1959 for the Priest River Experimental Forest; and in 1958 to 1960 for the Boise Basin Experimental Forest. The moisture of 6-inch-diam logs located on

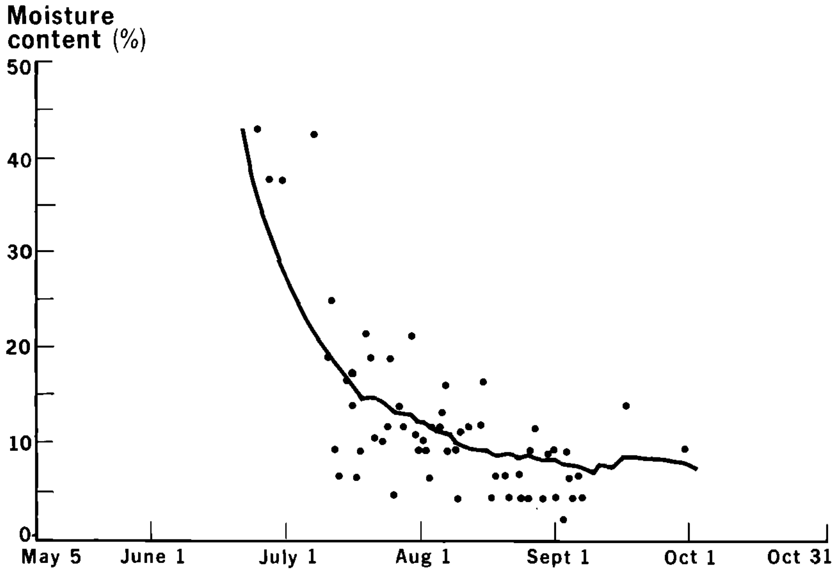

FIGURE 2. Comparison of predicted (line) and observed (points) moisture contents for Boise Basin in 1958.

racks in a clearcut were compared with calculated 1000-hour fuel moisture values (Brackebusch 1975). The time series of moisture was begun with the first observed moisture content of the season.

Priest River data included three sets of sample logs (1942 to 1949, 1950 to 1957, and 1958 to 1960). A single set of logs was used for the 3-year Boise Basin study. In all cases, the logs were western redcedar (*Thuja plicata* Donn ex D. Don). Although the weather measurements were consistent throughout the study, the method of weighing the logs to determine their moisture content changed in 1958. The new weighing system was less accurate and had lower resolution. In addition, the logs that were used beginning in 1958 were not as well seasoned as those of previous years.[1]

In the seasonal plot of a representative year from Priest River, predicted fuel moisture follows the seasonal moisture trend and also responds to rainfall periods (Fig. 1). Observed fuel moisture rose much higher than predicted during the rain periods, with precipitation amounts greater than 0.1 inch per day. The high readings could be attributed to free water held by capillary force in the numerous checks, particularly since the high moistures occurred only after substantial rainfall. When the high precipitation days were eliminated from statistical analysis, the absolute mean difference decreased from 1.7 to 0.2 percent fuel moisture, the root mean square difference decreased from 4.1 to 1.9 percent, and the correlation coefficient increased from 0.76 to 0.89 percent. A similar trend is seen for other years.

Predicted and observed fuel moistures were compared by using Priest River data prior to changing the weighing system. Even when high precipitation days were included, the greatest absolute mean difference was 2.9; the highest root mean square error was 5.7; and 9 of the 10 years had a correlation coefficient

[1] Personal communication from Arthur P. Brackebusch, Northern Region, USDA Forest Service, Missoula, Montana, March 1979.

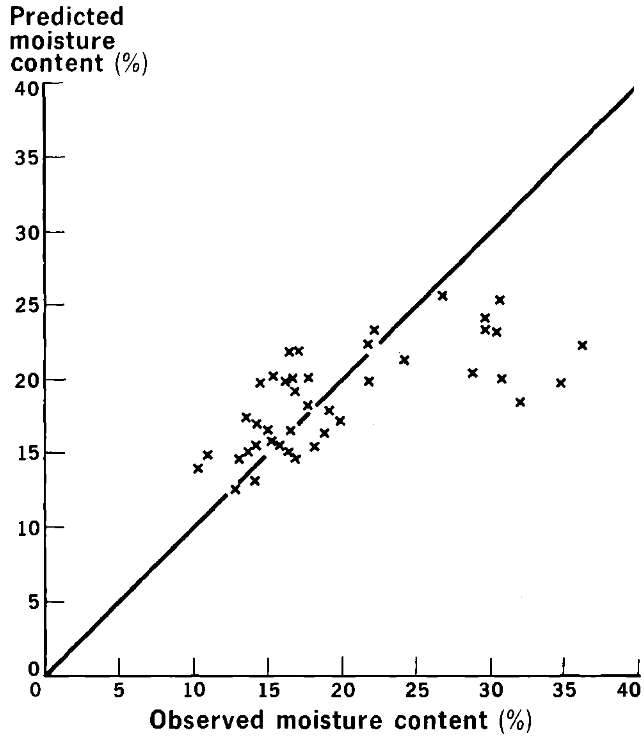

FIGURE 3. Independent Priest River data used to validate the regression equation for the seasonal starting value of 1000-hr timelag fuel moisture. Solid line represents a perfect fit line.

greater than 0.75. The correlation coefficient for all data from the 10 years combined was 0.78. This increased to 0.85 when the high precipitation days were not included.

The agreement of Boise Basin data is not as high, attributed in part to the change of weighing system and the poorly seasoned logs. Also, in fall 1957, the logs were transported from relatively moist conditions at Priest River to the drier Boise Basin. The moisture contents recorded at the beginning of the 1958 season were exceptionally high for Boise Basin. While the duration of precipitation controls water uptake of dead fuels, the amount of precipitation may be used to illustrate the high moisture content. Annual average precipitation is 24.5 inches at Boise Basin and 33.3 inches at Priest River. Note that even in this extreme case, the model tracked the observed moisture trend (Fig. 2).

Development of regression equation (7) for 1000-hour timelag fuel moisture needed at the beginning of the fire season was based on Priest River data for the years 1950 to 1958. An independent check of this equation was made for the years 1942 to 1949 and 1959 to 1960 (Fig. 3). The calculation uses monthly averages of daily weather data taken near the log site. An explanation for the model error at elevated moisture contents is not readily available since both the data used to develop the equation and data used to validate the equation showed similar characteristics.

A comparison of calculated daily 1000-hour moistures for an arid region (Gila Center, New Mexico) with a humid region (Libby, Montana) illustrates the importance of starting value calculations. A given month's starting value was calculated from monthly averages for the previous month, based on local Climatological Data publications (Gila Center calculations were based on Albuquerque

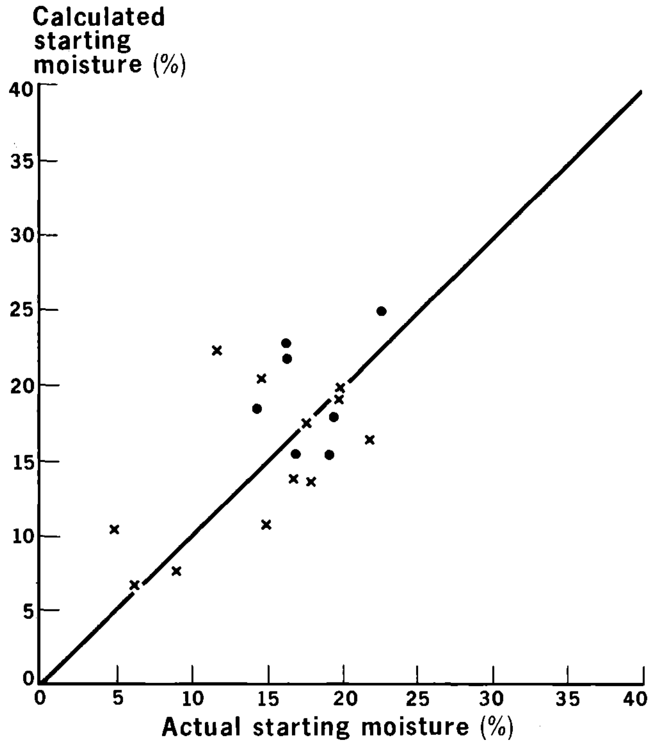

FIGURE 4. Comparison of the regression equation prediction for each month of the fire season, calculated by AFFIRMS, for Gila Center, New Mexico (×), and Libby, Montana (dots). Solid line represents a perfect fit line.

data; Libby calculations, on Missoula data). Comparison of resultant starting values with the corresponding calculated daily value indicates that this method provides a reasonable estimate of starting moisture content (Fig. 4).

SUMMARY

Techniques to calculate daily 1000-hour timelag fuel moistures using weather data were developed from theoretical concepts. The calculations are based on mean daily temperatures and humidities and the duration of precipitation in both snow and rain. These calculations were compared to the 6-inch-log data of the large-log study performed at the Priest River Experimental Forest and the Boise Basin Experimental Forest. Excellent agreement between observed and predicted moistures were obtained when all theoretical assumptions were met, that is, when a correlation coefficient of 0.85 was obtained. Even when assumptions were not met due to nonabsorbed free water, a correlation coefficient of 0.78 was obtained between predicted and observed moisture contents.

An equation to determine the seasonal starting value for 1000-hour timelag fuel moisture was developed. An independent data evaluation showed excellent agreement. Comparisons of predicted starting values for an arid and a humid climate showed that sufficient differences in calculated seasonal starting values exist.

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Errata

The Distribution of Root Length, and the Limits to Flow of Soil Water to Roots in a Dry Sclerophyll Forest, By B. A. Carbon, G. A. Bartle, A. M. Murray, and D. K. Macpherson, Forest Science 26(4):656–664 (December 1980).

In Table 1, page 658, the second line in the stub under the heading "Texture horizon" should read K_S (cm/day).

* * *

Is Succession in Hardwood Forests a Stationary Markov Process? by Clark S. Binkley, Forest Science 26(4):566–570 (December 1980).

In Table 1, page 569, the two main headings over the table body should read "Species class in 1937" (not 1967) and "Species class in 1967" (not 1977).