INFLUENCE OF WEATHER FACTORS ON MOISTURE CONTENT OF LIGHT FUELS IN FORESTS OF THE NORTHERN ROCKY MOUNTAINS [1]

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INTRODUCTION

The necessity of forest-fire protection is generally recognized in the United States. The tremendous damage done by forest fires each year to valuable timber, watershed cover, forest range, wildlife, recreational facilities, and personal property has impressed upon the people the need for preventing and controlling forest fires so far as this is humanly possible.

In the forests of northern Idaho and of Montana the fire-protection problem is particularly difficult, owing to the inflammable character of the forest vegetation and to the dryness of the summer weather. On the 23 million acres of national-forest land in this area, during the 10-year period 1925–34 there occurred a yearly average of 1,356 fires, which burned over 114,000 acres, caused damage totaling nearly three-quarters of a million dollars, and required expenditure of a similar amount for control.

Fire-control experience has shown that in this northern Rocky Mountain region approximately 50 percent of the area burned and 35 percent of the suppression costs result from only 1 percent of the fires.

Obviously, in this region satisfactory fire control can be attained only if the fire-protection organization succeeds in suppressing fires while they are still small. In efforts toward this end, administrative officers are aided by knowledge of current forest-fire danger.[3] A complete understanding of fire danger from day to day is difficult to obtain because many factors are involved, including season of year, activity of fire-starting agencies, topography, character of green vegetation, weather, fuel type, fuel volume, and fuel moisture content. By making observations or measurements of several of the most important factors and properly integrating them, however, the forest protectionist can determine the relative fire danger existing at a given time and place. In this way he can learn whether his force should be temporarily expanded or reduced, and how it should be distributed over the area for which he is responsible. In addition, through a knowledge of the influence of given factors on fire danger the protectionist is assisted in interpreting weather forecasts and thus in preparing for all classes of fire danger that are likely to arise.

[1] Received for publication July 29, 1935: issued February 1936.

[2] The writer is indebted to F. X. Schumacher, of the Division of Silvical Research, Forest Service, for guidance in planning the statistical analysis involved in this study

[3] "Forest fire danger" as used here is a general term expressing the sum total of the factors that determine whether fires will start, spread, and do damage.

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SIGNIFICANCE OF MOISTURE CONTENT OF FOREST FUELS

Fuel-moisture content alone serves as a criterion of forest-fire danger. The wetness or dryness of forest fuels largely determines their inflammability or ease of ignition and the rate of spread of forest fire. Obviously, each fuel must be heated to a certain temperature before combustion results, and anything that retards this heating reduces fire danger. Water in the fuels absorbs heat before it is driven off in the form of vapor; consequently it delays the raising of fuel temperatures to the kindling point. Knowledge of the relation of the moisture content of the common forest fuels to their inflammability, or to the rate of spread of fire, or to both, is essential in determining current fire danger.

The moisture content of lightweight fuels such as duff and small branch wood is particularly important because of their wide-spread distribution in almost all forest types and because they serve as carriers of fire from tree to tree and from log to log. Duff commonly composes a greater part of the surface layer of the forest floor than any other single fuel.

Show (*9*),[4] Larsen (*7*), Stickel (*10, 11*), and Gisborne (*3*) proved the important relation of moisture content to the inflammability of duff [5] by making burning tests. The latter two workers tested in detail the ease of igniting duff of given moisture content with different firebrands. Gisborne, working with undisturbed duff in western white pine (*Pinus monticola*) forests in northern Idaho, concluded that whenever the duff has less than 10 percent moisture content it can be ignited by any firebrand producing heat equal to that of an ordinary match, that at more than 13 percent moisture the duff is generally immune to ignition by burning matches, and that camp fires can ignite the duff and cause fire to spread through it whenever it contains less than 18 percent moisture. On the basis of these findings and of general observation, Gisborne defined the following six degrees of susceptibility of the top layer of duff to ignition by various common firebrands:

Degree of susceptibility:	*Moisture content (percent)*
Noninflammable	More than 25.
Very low inflammability	25 to 19.
Low inflammability	18 to 14.
Medium inflammability	13 to 11.
High inflammability	10 to 8.
Extreme inflammability	7 to 0.

Stickel (*10*) made a detailed investigation in the Adirondack Mountains to determine the moisture content necessary to prevent ignition of duff by matches, cigarette butts, pipe heels, locomotive sparks, and small camp fires. His results, from 370 tests, are summarized in table 1.

[4] Reference is made by number (italic) to Literature Cited, p. 905.

[5] In this discussion the term "duff" applies to the surface layer of the forest floor, that is, to the "litter", which is made up of vegetable-matter deposits only slightly decomposed.

TABLE 1.—*Surface duff-moisture contents at which various firebrands are effective* [1]

Degree of hazard [2]	Surface duff moisture content, percent	Firebrands effective
Extreme	Less than 6	Cigarettes, locomotive sparks, pipe heels, matches, and camp fires.
High	6 to 10	Locomotive sparks, pipe heels, matches, and camp fires.
Medium	11 to 16	Pipe heels, matches, and camp fires.
Low	17 to 22	Matches and camp fires.
Very low	23 to 29	Camp fires.[3]
Generally safe	30 or more	None.

[1] According to findings of Stickel (*10*).
[2] "Hazard", in Stickel's classification, has the same meaning as is attached in this paper to "forest-fire danger" (see footnote 3, p. 885).
[3] Duff at edge will smolder, but fire will not spread much.

Rate of spread of forest fire has definitely been shown to depend principally upon fuel-moisture content. The Quartz Creek fire of 1926 (*2*) and the Freeman Lake fire of 1931 (*4*), both in northern Idaho, made their longest runs on days when duff moisture was exceptionally low. The latter fire, which spread at an average rate of 1,600 acres per hour for 12½ hours, began at a time when the duff-moisture content was about 5 percent. In no recorded instance has a "blow-up" occurred when the moisture content of lightweight fuels was relatively high.

DETERMINANTS OF FUEL MOISTURE CONTENT

The several weather elements, acting together, are the most important determinants of forest fuel moisture content. When the weather is wet, the fuels are wet or tend to become so; and dry weather produces dry conditions in the fuels. The changes, of course, require more or less time, the lag depending upon how wet or dry the fuels were to begin with. In the northern Rocky Mountains, after a heavy rain a week or more of hot, drying weather may be required to produce extreme danger.

The moisture content of light fuels such as duff and small branch wood bears an especially close relation to current weather. Duff, in particular, because of its loose distribution and porous structure, picks up or loses moisture rapidly when atmospheric conditions change.

Differences in the moisture contents of similar fuels on parts of the same area may be due in part to weather variations between one place and another, but no doubt are due principally to differences in degree of exposure of the fuels. A dense forest canopy intercepts most of the direct rays of the sun and reduces wind movement, thereby lowering temperature and evaporation and increasing humidity beneath it (*5*). Fuel moistures, consequently, are higher under dense canopies than they are on burned-over or clear-cut areas fully exposed to sun and wind.

METHODS AND CONDITIONS OF FIELD STUDY

The study discussed here has dealt for the most part with duff-moisture content in its relation to current weather. It has dealt also with moisture content of branch wood one-half inch in diameter in its relation to weather. These relations were observed under different forest-canopy conditions.

In this study duff-moisture measurements have been confined to the uppermost ½-inch layer, because when the moisture content of this layer is low fire may spread through it rapidly even if the average moisture content of the entire forest floor is high.

Measurements of weather factors and fuel moisture have been made on three exposures at the Priest River branch of the Northern Rocky Mountain Forest and Range Experiment Station, in northern Idaho. Beginning in 1924, observations were taken on an area from which all trees had been removed; on an area where timber cutting had reduced the forest canopy by about half, the principal tree species of the remaining stand being western hemlock (*Tsuga heterophylla*); and in a dense stand of western white pine near the base of

FIGURE 1.—Clear-cut station, fully exposed to weather.

a northwest slope. These areas were approximately three-quarters of a mile apart. In 1930 the original half-cut and full-timbered stations were abandoned, and new ones established on a bench within 1,400 feet of the clear-cut station. On the new half-cut station, the residual stand is similar in composition to that on the one abandoned. The new full-timbered station is occupied by the climax western white pine type, in which western hemlock and western red cedar (*Thuja plicata*) predominate. Comparative light values taken at the instrument exposures by Haig [6] are shown in table 2. The clear-cut station, and the half-cut and full-timbered stations in use from 1930, are shown in figures 1, 2, and 3, respectively.

[6] HAIG, I. T. CERTAIN FACTORS CONTROLLING INITIAL SEEDLING ESTABLISHMENT IN WESTERN WHITE PINE STANDS. 1935. (Unpublished doctor's dissertation. Copies on file at Yale Univ. School of Forestry, New Haven, Conn., and Northern Rocky Mountain Forest and Range Expt. Sta., Missoula, Mont.)

FIGURE 2.—Half-cut station; residual stand is composed chiefly of western hemlock.

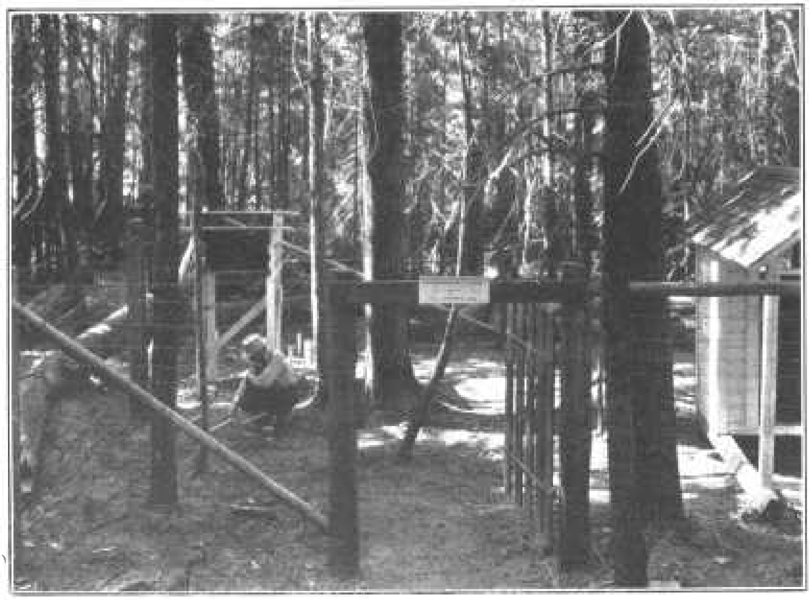

FIGURE 3.—Full-timbered station; the dense virgin stand is composed chiefly of western hemlock and western red cedar.

TABLE 2.—*Light values on half-cut and full-timbered areas in use from 1930, as determined with different instruments*

Instrument	Light, in terms of full sunlight, on—	
	Half-cut area	Full-timbered area
	Percent	*Percent*
Clements photometer	24	4
Shirley thermopile	23	3
Livingston black and white spheres	26	5
Average	24.3	4

Careful study revealed that the old and new stations were nearly enough alike to justify joint analysis of records obtained before and after 1930.

Simultaneous measurements of weather factors and duff-moisture content on the clear-cut, half-cut, and full-timbered areas were begun in June 1924. They were made daily at 4:30 p. m. Air temperature, relative humidity, precipitation, evaporation, and temperature of the dew point were the weather elements measured in 1924. Other elements were added later. Table 3 lists the factors investigated and shows in what years measurement of each factor was begun on the three areas, respectively. Beginning with 1925, twice-daily measurements were made at all stations throughout the fire season, at approximately 9 a. m. and 4:30 p. m. These two hours were selected in order to sample extremes, preliminary investigation having indicated that fuel moisture normally was greatest between 7 and 9 a. m. and least at about 4:30 p. m. The dates on which measurements were begun and ended each year were not fixed. In general, measurements were begun in April or May, before the fire season actually started, and were terminated in late September or early October after the fire season definitely came to an end.

TABLE 3.—*Fuel-moisture and weather factors studied, and years in which measurement of each was begun on the three study areas, respectively*

Factor	Year in which measurements were begun on—		
	Clear-cut area	Half-cut area	Full-timbered area
Fuel moisture content:			
Duff moisture	1924	1924	1924
½-inch wood moisture	1929	1929	1929
Weather elements and associated factors:			
Maximum air temperature	1924	1930	1930
Current air temperature	1924	1924	1924
Minimum air temperature	1924	1930	1930
Maximum duff temperature	1930	1930	1930
Temperature of the dew point	1924	1924	1924
Current relative humidity	1924	1924	1924
Minimum relative humidity	1924	1930	1930
Average relative humidity	1924	1930	1930
Wind	1930	1930	1930
Precipitation	1924	1930	1930
Evaporation	1924	-----	-----
Number of days since 0.01 inch of precipitation	1924	1924	1924
Number of days since .10 inch of precipitation	1924	1924	1924
Number of days since .20 inch of precipitation	1924	1924	1924
Number of days since .30 inch of precipitation	1924	1924	1924
Number of days since .40 inch of precipitation	1924	1924	1924

ANALYSIS OF DATA, AND APPLICATION OF RESULTS OF ANALYSIS

Gross correlations indicate the forest-fuel moistures that normally exist at given air temperatures and humidities; they fail, however, to show the relative or net influence of temperature or of humidity on fuel-moisture content. None of the weather elements acts independently of the others. Hence, in order to determine fundamental relations between fuel-moisture content and the weather it was necessary to subject weather and fuel-moisture data to multiple-correlation analysis.

METHOD OF ELIMINATING CURVILINEARITY

A preliminary multiple-correlation study involving duff moisture as the dependent variable and several weather elements as the independent variables produced, in all cases, curvilinear regressions.

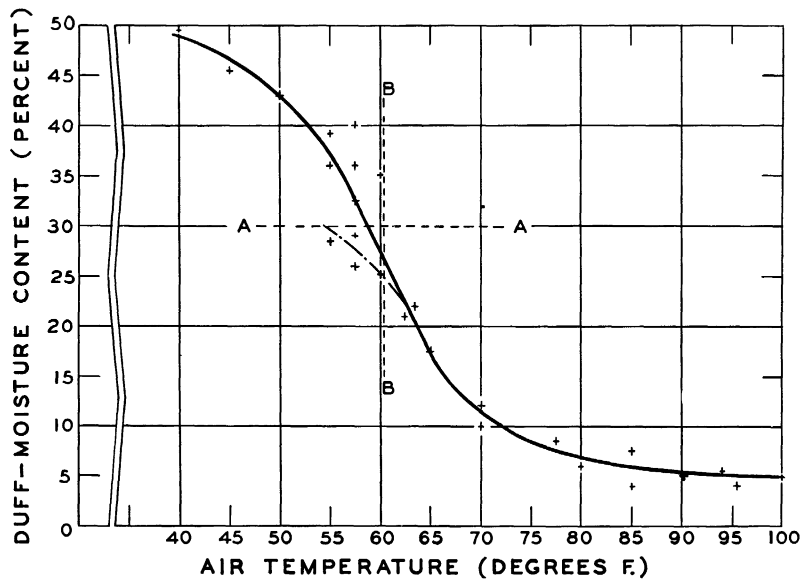

FIGURE 4.—Hypothetical regression of duff-moisture content on air temperature.

In multiple-correlation problems it is desirable to obtain algebraic expression of regressions whenever possible, because they are the simplest to compare and interpret and are not susceptible to the personal error associated with fitting freehand curves. The curvilinearity of these regressions was due to the fact that the instrument used to measure duff moistures does not show values greater than 50 percent. Direct elimination of observations of duff-moisture content amounting to, say, 30 percent or more inevitably lessens the average slope of the regression curve. These data can be eliminated without altering the slope, however, by placing a limit on an independent variable. An illustration of the effects of these two procedures follows: In figure 4 if all observations of duff moisture greater than 30 percent—that is, all the points above line *A*—are directly eliminated, the upper end of the line of best fit is changed from its former position to the one shown by the dash-dot line. Limitation of the dependent variable, then, has changed the slope of the regression curve. However, if all observations made when air temperature was 60° F. or lower—that is, all points to the left of line *B*—are rejected all duff moistures of 30 percent or more are eliminated from the correlation without causing a change in the slope of the regression curve.

If study is restricted to observations made on the clear-cut area 2 or more days after 0.01 inch of precipitation, and on the half-cut and full-timbered areas 5 or more days and 6 or more days, respectively, after 0.01 inch of precipitation, all duff moistures of 30 percent or more are eliminated. This removes the curvilinearity in the net regressions due to restriction of the dependent variable to 50 percent. It is logical to confine the study to duff moistures of less than 30 percent, because when duff contains 30 percent or more moisture fire danger does not exist.

SELECTION OF MOST IMPORTANT VARIABLES

As is shown in table 3, data on 16 weather elements were available for analysis. This large number of variables cannot be handled conveniently by the usual correlation methods. It was thought possible that certain of these factors contribute nothing of significance to the final multiple-correlation coefficient, although each shows a definite relation to fuel moisture when correlated with it separately. For these reasons, measures were taken to select those weather elements that contributed most to the multiple correlation.

Analysis of a random sample of 130 sets of afternoon measurements for the clear-cut area according to the method developed by Kincer and Mattice (*6*) showed that the factors having the greatest effect on fuel moisture were current air temperature and relative humidity. Maximum duff temperature and evaporation rate were correlated almost as closely with fuel moisture as current air temperature and relative humidity, respectively. Factors having comparatively small influence on fuel moisture were temperature of the dew point, number of days since 0.01 or 0.20 inch of precipitation, and wind. These variables were retained for further investigation in preference to mean and minimum relative humidity, for example, because the latter are highly correlated with current relative humidity.

On the basis of all the available afternoon records for the clear-cut area that were made more than a day after 0.01 inch of precipitation, gross-correlation coefficients were computed for duff moisture as the dependent variable with each of the following eight factors as independent variables: Current relative humidity, current air temperature, maximum duff temperature, evaporation, temperature of the dew point, number of days since 0.01 inch of precipitation, wind, and number of days since 0.20 inch of precipitation. The results are given in table 4. Because wind and number of days since 0.20 inch of precipitation were not found to be significantly correlated with either the dependent variable, duff moisture, or with any of the other variables tested, they were dropped from consideration.

TABLE 4.—*Gross-correlation coefficients*[1] *for all combinations of duff-moisture content (X) on clear-cut area and eight weather factors*

Correlation coefficient r	Numerical value	Correlation coefficient r	Numerical value	Correlation coefficient r	Numerical value	Correlation coefficient r	Numerical value
XA	+0.660	AD	−0.608	BH	+0.103	EF	−0.227
XB	−.576	AE	+.597	CD	+.734	EG	−.169
XC	−.552	AF	+.229	CE	−.053	EH	−.049
XD	−.535	AG	−.051	CF	+.064	FG	−.011
XE	+.312	AH	−.058	CG	−.010	FH	+.161
XF	−.146	BC	+.784	CH	+.001	GH	−.093
XG	−.037	BD	+.740	DE	−.007		
XH	−.028	BE	−.020	DF	+.035		
AB	−.727	BF	+.133	DG	+.088		
AC	−.597	BG	−.121	DH	−.193		

[1] Based on 226 sets of afternoon observations taken 1 or more days after 0.01 inch of precipitation. Explanation of symbols: A=relative humidity; B=air temperature; C=maximum duff temperature; D=evaporation; E=temperature of the dew point; F=number of days since 0.01 inch of precipitation; G=wind; H=number of days since 0.20 inch of precipitation.

JOINT CORRELATION

When a multiple correlation of duff moisture with air temperature and relative humidity was made, a joint relation was evident. A joint relation of variables is the relation existing when the change in a dependent variable that corresponds with a change in one independent variable depends in part upon the magnitude of a second

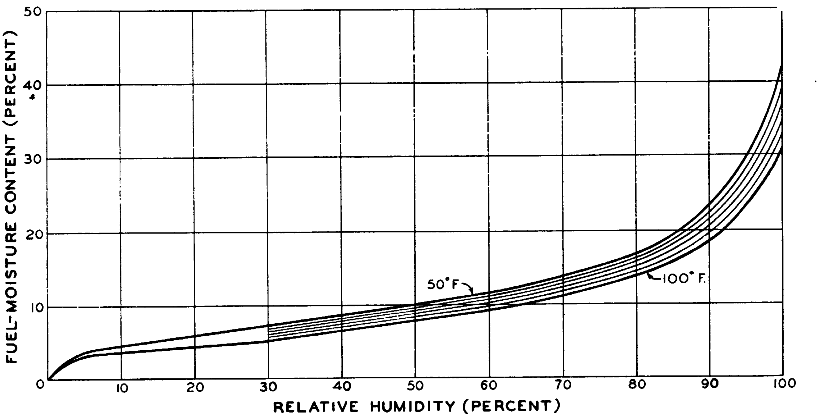

FIGURE 5.—Curve of moisture contents of coniferous duff and branch wood in equilibrium with air temperature and humidity (as determined by M. A. Dunlap).

independent variable. The equilibrium relations between fuel moisture and relative humidity at different air temperatures determined by Dunlap,[7] of the Forest Products Laboratory, and shown in figure 5 also indicate a joint relation.

The standard linear-regression equation of the form

$$DM = aT + bRH + K \qquad (1)$$

in which

DM=Duff-moisture content
T=Air temperature
RH=Relative humidity

and

a, b, K=Constants

[7] DUNLAP, M. A. THE RELATION OF HUMIDITY TO THE MOISTURE CONTENT OF FOREST FIRE FUELS. 1924. [Unpublished manuscript. U. S. Dept. Agr., Forest Prod. Lab., Madison, Wis.]

does not show this relation. This type of equation results in parallel regression lines that do not fit the data except when all three variables are at their mean values. In other words, it represents the change in duff moisture caused by a change in relative humidity as constant regardless of air temperature. In order to reveal the true relation of air temperature and relative humidity to duff moisture, joint-correlation methods must be used.

A regression equation of the type

$$DM=a\left(\frac{RH}{T}\right)+K \tag{2}$$

was found to fit the data, as is clearly illustrated in figures 6 and 7. The lines of regression in figure 6 represent values computed separately

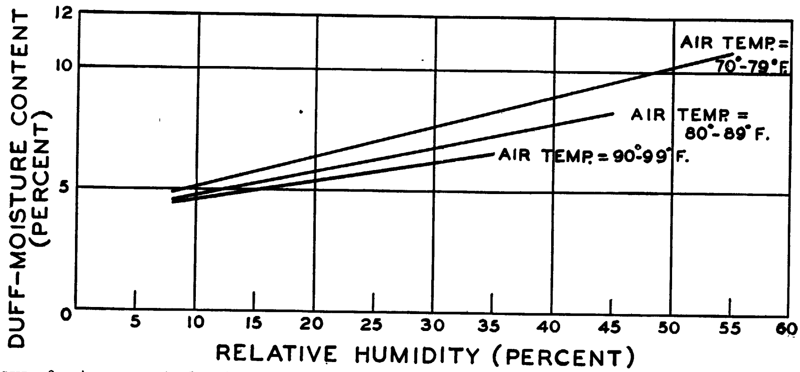

FIGURE 6.—Average actual moisture content of duff on the clear-cut area at given relative humidities and air temperatures. (Basis, 206 sets of observations taken at 4:30 p. m.)

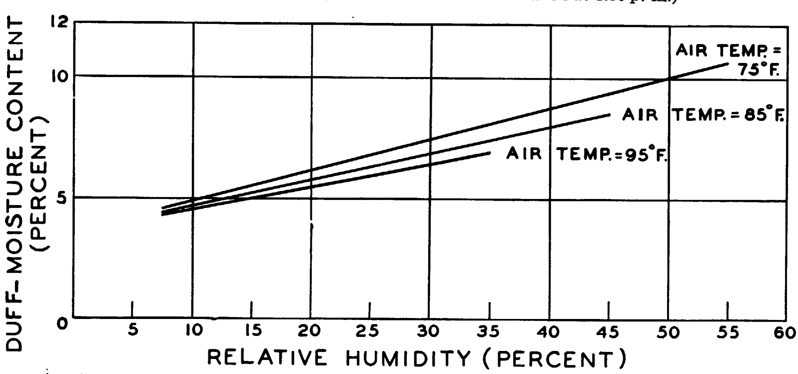

FIGURE 7.—Average moisture content of duff on the clear-cut area at given relative humidities and air temperatures, as estimated by use of the regression equation $DM=9.64\left(\frac{RH}{T}\right)+3.55$. (Basis, 226 observations taken at 4:30 p. m.)

for each of the temperature classes shown; those in figure 7 were located by substituting values of temperature and humidity in equation 2.

The use of the term $\frac{RH}{T}$ is explained as follows:

Relative humidity is the ratio between the quantity of water vapor in a unit of space and the maximum quantity that unit of space can hold, temperature and pressure remaining constant. Absolute humidity is the actual quantity of moisture in a unit of space, usually expressed in grains per cubic foot. Let

AH = Absolute humidity
AH_s = Absolute humidity at saturation.

Then, by definition $RH=\frac{AH}{AH_s}$ when temperature and pressure are constant.

But AH_s depends entirely on T. Then $RH=\frac{AH}{f(T)}$, where $f(T)=$ some function of T, or $f(T)$ $(RH)=AH$. If $f(T)=\frac{1}{T}$, then $\frac{RH}{T}=AH$. In other words, if $f(T)$ equals $\frac{1}{T}$, the reciprocal of temperature times relative humidity equals absolute humidity.

When the product of $f(T)\times RH$ is absolute humidity in grains per cubic foot, $f(T)$ does not vary as $\frac{1}{T}$ does, but equals the values shown in column 2 of table 5. Consequently, when $\frac{RH}{T}$ (which is the same as $\frac{1}{T}\times RH$) is equated to absolute humidity the resulting values are not in units of grains per cubic foot, or in any other units that can be identified. They are converted into grains per cubic foot, however, if multiplied by the values given in columns 3 and 6 of table 5.

Use of $\frac{RH}{T}$ as a variable was very advantageous in the correlations of this study because (1) when this term is used as a variable the regression equation actually fits the data; (2) the term is an index of absolute humidity; and (3) actual measurements of absolute humidity were not available in a form usable for the analysis, which was made by machine sorts and tabulations of punch cards. Owing to the availability of complete and lengthy records of temperature and relative humidity, great use can be made of the results of a correlation involving $\frac{RH}{T}$ as a variable. One advantage of a method of estimating fire danger through use of this variable is that it makes possible fire-danger ratings, for many stations, for past seasons during which records were made at those stations of air temperature and relative humidity but not of duff moisture.

TABLE 5.—*The values of f(T) in the equation* $f(T) \times RH = AH$, *and the values of X in the equation* $X\left(\frac{RH}{T}\right) = AH$, *that give absolute humidities in grains per cubic foot*

Air temperature (*T*, °F.)	Values that give absolute humidities in grains per cubic foot		Air temperature (*T*, °F.)	Values that give absolute humidities in grains per cubic foot	
	f(T), in the equation $f(T) \times RH = AH$	*X*, in the equation $X\left(\frac{RH}{T}\right) = AH$		*f(T)* in the equation $f(T) \times RH = AH$	*X*, in the equation $X\left(\frac{RH}{T}\right) = AH$
50	0.04076	2.038	80	0.10934	8.747
55	.04849	2.667	85	.12736	10.826
60	.05745	3.447	90	.14790	13.311
65	.06782	4.408	95	.17124	16.268
70	.07980	5.586	100	.19766	19.766
75	.09356	7.017			

If $\frac{RH}{T}$ is used as an independent variable in the place of relative humidity the gross correlation with duff moisture is equally complete, as is shown by the coefficient $r_{X.A}$ in table 6, which gives gross-correlation coefficients for all combinations of duff moisture and the six weather factors having the greatest influence upon it.

TABLE 6.—*Gross-correlation coefficients*[1] *for all combinations of duff moisture* (*X*) *on clear-cut area and the six weather factors most important in relation to it*

Correlation coefficient *r*	Numerical value	Correlation coefficient *r*	Numerical value	Correlation coefficient *r*	Numerical value	Correlation coefficient *r*	Numerical value
XA	+0.672	*AB*	−0.778	*BD*	+0.740	*DE*	−0.007
XB	−.576	*AC*	−.635	*BE*	−.020	*DF*	+.035
XC	−.552	*AD*	−.657	*BF*	+.133	*EF*	−.227
XD	−.535	*AE*	+.464	*CD*	+.734		
XE	+.312	*AF*	−.210	*CE*	−.053		
XF	−.146	*BC*	+.784	*CF*	+.064		

[1] Based on 226 sets of afternoon observations taken 1 or more days after 0.01 inch of precipitation. Explanation of symbols: *A*=relative humidity divided by air temperature; *B*=air temperature; *C*=maximum duff temperature; *D*=evaporation; *E*=temperature of the dew point; *F*=number of days since 0.01 inch of precipitation.

GROSS AND MULTIPLE CORRELATIONS

In an endeavor to find what group of variables bear the closest relation to duff moisture, correlation coefficients were computed for all possible combinations of 2, 3, 4, 5, and 6 weather factors as independent variables with duff-moisture content as the common dependent variable. The multiple-correlation coefficients were computed from the gross *r*'s according to the method outlined by Wallace and Snedecor (*12*). They are given in table 7.

TABLE 7.—*Gross- and multiple-correlation coefficients*[1] *for all combinations of duff moisture (X) on clear-cut area with the six weather factors most important in relation to it*

Correlation coefficient *r*	Numerical value	Correlation coefficient *R*	Numerical value	Correlation coefficient *R*	Numerical value
XA	+0.672	*X.AC*	0.691	*X.ACE*	0.694
XB	−.576	*X.AD*	.683	*X.ACD*	.693
XC	−.552	*X.AB*	.677	*X.ACF*	.692
XD	−.535	*X.AF*	.672	*X.ABC*	.691
XE	+.312	*X.AE*	.672	*X.ADE*	.686
XF	−.146	*X.BE*	.650	*X.ABD*	.684
		X.CE	.620	*X.ADF*	.684
		X.DE	.617	*X.ABE*	.681
		X.BC	.598	*X.ABF*	.677
		X.BD	.598	*X.AEF*	.672
		X.CD	.584	*X.BDE*	.671
		X.BF	.580	*X.BCE*	.666
		X.CF	.563	*X.CDE*	.654
		X.DF	.550	*X.BEF*	.650
		X.EF	.322	*X.CEF*	.623
				X.DEF	.620
				X.BCD	.608
				X.BDF	.604
				X.BCF	.604
				X.CDF	.596

Correlation coefficient *R*	Numerical value	Correlation coefficient *R*	Numerical value	Correlation coefficient *R*	Numerical value
X.ACDE	0.697	*X.ABCDE*	0.697	*X.ABCDEF*	0.697
X.ABCE	.694	*X.ACDEF*	.697		
X.ACEF	.694	*X.ABCEF*	.694		
X.ABCD	.693	*X.ABCDF*	.693		
X.ACDF	.693	*X.ABDEF*	.690		
X.ABCF	.692	*X.BCDEF*	.677		
X.ABDE	.690				
X.ADEF	.686				
X.ABDF	.684				
X.ABEF	.681				
X.BCDE	.676				
X.BDEF	.671				
X.BCEF	.666				
X.CDEF	.656				
X.BCDF	.615				

[1] Based on 226 sets of afternoon observations taken 1 or more days after 0.01 inch of precipitation. Explanation of symbols: *A*=relative humidity divided by air temperature; *B*=air temperature; *C*=maximum duff temperature; *D*=evaporation; *E*=temperature of the dew point; *F*=number of days since 0.01 inch of precipitation.

TEST OF SIGNIFICANCE OF DIFFERENCE BETWEEN CORRELATION COEFFICIENTS

Table 7 gives evidence that the single variable $\frac{RH}{T}$, or "absolute-humidity index", as it is hereafter called, is associated with duff moisture almost as closely as all six of the independent variables taken together. Evidence to this effect includes the fact that the difference between $r_{X.A}$ and $R_{X.ABCDEF}$ is only 0.025. This difference, when tested according to a method outlined by Russell (*8*), was found to be slightly significant. The procedure follows:

r^2_{XA}=Square of the coefficient of the correlation between duff moisture (*X*) and relative humidity divided by temperature (*A*).

$R^2_{X.ABCDEF}$=Square of the coefficient of the multiple correlation between duff moisture (*X*) and six weather factors.

N=Number of observations.

Term 1$=1-R^2_{X.ABCDEF}$

Term 2$=R^2_{X.ABCDEF}-r^2_{XA}$

If we multiply term 1 by $N\sigma^2_X$ (which is the sum of squares for variable X), the product equals the sum of squares for X independent of the part associated with variables A, B, C, D, E, and F. This sum can be considered as the unexplained sum of squares, or "error." If we multiply term 2 by $N\sigma^2_X$ the product is equal to the sum of squares for X associated with variables B, C, D, E, and F.

The test of significance consists in comparing the variance, or mean square, derived from term 2 with the variance derived from term 1. If the variance of X explained by the variables B, C, D, E, and F is significantly greater than error, then the correlation involving all seven variables is really higher than the simple correlation involving variables X and A.

When such a test of significance is made in practice, the actual values of terms 1 and 2 are used as "relative" sums of squares. Since both terms are multiplied by the same value ($N\sigma^2_X$), their relative values are not changed, and the final test of significance (table 8) is based upon the mean squares.

TABLE 8.—*Computation of relative mean squares to be used in significance test*

Relative sums of squares	Degrees of freedom	Relative mean squares
$1-R^2_{X.ABCDEF}$, or 0.5142	N-7, or 219	0.002348
$R^2_{X.ABCDEF}-r^2_{XA}$, or 0.0342	5	.006840
$1-r^2_{XA}$, or 0.5484	N-2	----------

The mean squares are obtained by dividing the relative sums of squares by the degrees of freedom associated with them, respectively.

The variance of X associated with B, C, D, E, and F can be compared with error by means of the "z test" developed by Fisher (*1*). The value of z is the difference between the natural logarithms of the two standard deviations; or, in terms of relative mean squares,

$$z=\frac{1}{2}\log_e\left(\frac{0.006840}{0.002348}\right)=0.5346$$

The probability, P, of this value's being exceeded by chance is 0.015, as determined from Fisher's tables with the degrees of freedom shown in table 8. (As is shown by Fisher's tables, z=0.3974 and 0.5522 when P=0.05 and 0.01, respectively.)

According to ordinary statistical practice, P must be 0.05 or less if two variances are to be considered significantly different. In more refined tests of significance, P must be 0.01 or less. In this comparison the odds are slightly greater than 1 to 100 that the observed difference is due to chance. While the influence of variables B to F is probably significant, the inclusion of these variables for the sake of a further reduction in the remaining variance of about 3 percent is impractical.

ESTIMATES OF DUFF MOISTURE FROM ABSOLUTE-HUMIDITY INDEX FOR CLEAR-CUT AREA

The regression equation given in the legend of figure 8 and the regression line shown in the figure, which are based on values computed by standard methods from all available afternoon measurements for the clear-cut area, provide a means of estimating duff moisture content from air temperature and relative humidity combined in the form of the absolute-humidity index. The correlation coefficient for these two variables was found to be +0.62; since r^2 equals 0.38, it is evident that only 38 percent of the variation in duff moisture is explained by the absolute-humidity index. Also, the standard error of estimate is ±2.49 percent. Thus, large errors are necessarily associated with single estimates of duff moisture based on the absolute-humidity index. However, the standard error of an average of estimates varies in inverse proportion with the square root of the number of estimates averaged. Thus an average of 100 estimates of duff moisture has a standard error of ±0.25 percent, and an average of 50 estimates has a standard error of ±0.35 percent and hence is acceptable for use in rating the severity of a fire season.

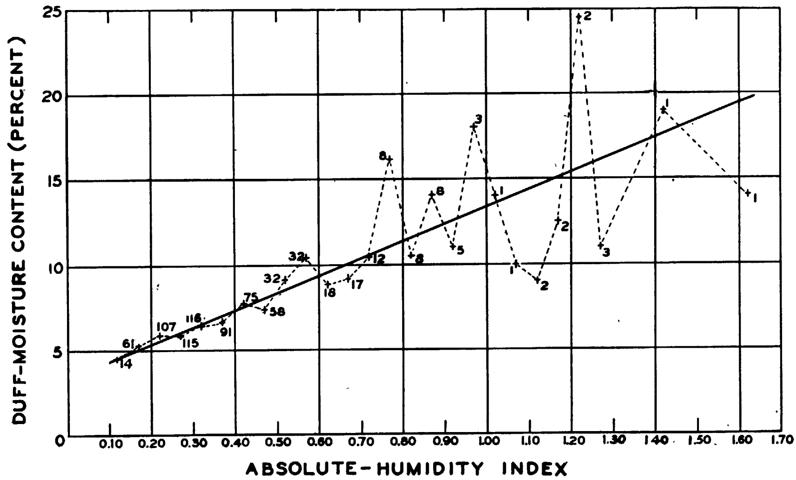

FIGURE 8.—Duff moisture and absolute-humidity index $\left(\frac{RH}{T}\right)$ on clear-cut area. (Basis, all available afternoon data, 793 observations taken at 4:30 p. m.) A=Relative humidity divided by temperature; X=duff moisture content; correlation coefficient (r_{XA})=+0.62; standard error of estimate $(S_{X.A})$=±2.49 percent; regression equation is $X=10.00A+3.40$.

The low correlation and its high standard error of estimate preclude any possibility of substituting the simple measurement of temperature and relative humidity for the more difficult measurement of duff-moisture content in field practice. That is, duff moisture cannot be estimated from measurements of these two atmospheric factors with a degree of accuracy satisfactory for forest-protection purposes. Also, this method of estimating is entirely inapplicable on the day of a rain or on the day following a rain.

CORRELATIONS BETWEEN DUFF-MOISTURE CONTENT AND ABSOLUTE-HUMIDITY INDEX FOR HALF-CUT AND FULL-TIMBERED AREAS

Correlations between duff-moisture content and the absolute-humidity index are somewhat lower for the half-cut and full-timbered areas than for the clear-cut area. High fuel moistures tend to prevail on shaded areas. As is seen from figure 5, small changes in temperature and relative humidity have a greater effect on high fuel moistures than on low ones. As a result, no doubt duff-moisture content is in equilibrium with the weather less often on timbered sites than in the open. Forest cover smooths out rapid fluctuations in weather much less than it retards the drying-out process in the fuels.

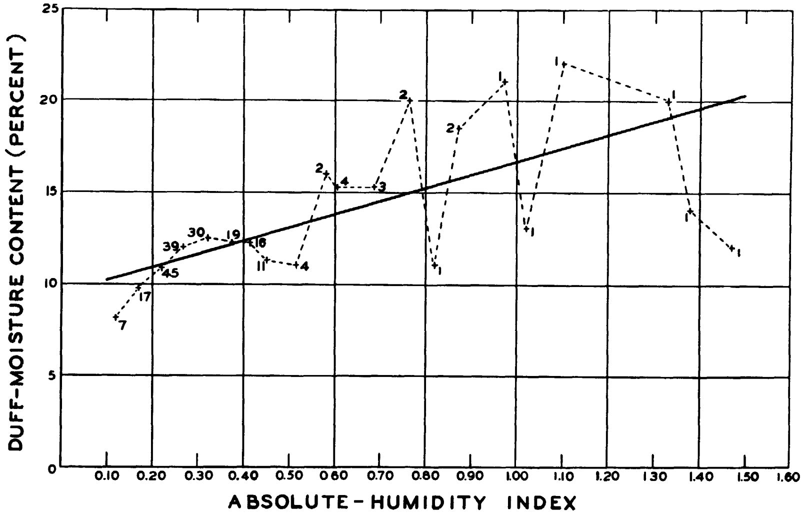

FIGURE 9.—Duff moisture and absolute-humidity index $\left(\frac{RH}{T}\right)$ on half-cut area. (Basis, 208 observations taken at 4:30 p. m. not less than 5 days after 0.01 inch of precipitation.) A=Relative humidity divided by temperature; X=duff moisture content; correlation coefficient $(r_{X.A})=+0.47$; standard error of estimate $(S_{X.A})=\pm2.78$; regression equation is $X=7.25A+9.41$.

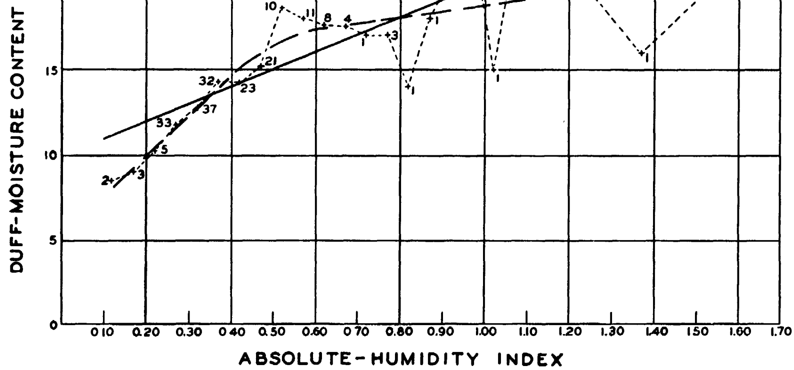

FIGURE 10.—Duff moisture and absolute-humidity index $\left(\frac{RH}{T}\right)$ on full-timbered area. (Basis, 201 observations taken at 4:30 p. m., not less than 6 days after 0.01 inch of precipitation.) For linear regression, correlation coefficient $(r_{X.A})=+0.50)$ standard error of estimate $(S_{X.A})=\pm3.61$, and regression equation is $X=10.23A+9.90$; for curvilinear regression, correlation index $(\rho_{X.A})=0.59$, and standard error of estimate=±3.34 percent.)

Figures 9 and 10 show regressions, correlation coefficients, and standard errors of estimate computed from the afternoon data for the half-cut and full-timbered sites after elimination of all observations made less than 5 days and less than 6 days, respectively, after 0.01 inch of precipitation.

On inspection of figures 9 and 10 a legitimate question arises, especially in the latter case, as to whether the curve of best fit is a straight line. A curve line was fitted to the data in figure 10 and its correlation index, symbolized by ρ, was found to be +0.59. A test of significance performed by Russell's method, previously described, revealed that there is no real difference between the correlation coefficient for the linear regression and the correlation index for the curve. Hence, the fit of the straight-line regression is satisfactory.

Correlations between duff moisture and the absolute-humidity index for the half-cut and full-timbered areas are of little practical value because of the high standard errors of estimate and because such correlations cannot be used until 5 days and 6 days, respectively, after 0.01 inch of precipitation.

CORRELATION OF DUFF MOISTURE WITH ABSOLUTE-HUMIDITY INDEX ON BASIS OF UNRESTRICTED DATA

The most usable method of estimating duff moisture from the absolute-humidity index would be one that could be applied on rainy days and on days immediately following rainy days, as well as at other times. By any method now available, little seems to be gained by making a correlation of duff moisture with the absolute-humidity index on the basis of data including measurements taken during and soon after rain. The effect of such procedure is to make the regression curvilinear. By the addition of free water to duff during rainy periods the duff-moisture content is increased much more than it could be increased by atmospheric humidity, even the increased humidity existing during such periods.

By inclusion of rainy-weather data in the basis of a correlation of duff moisture with absolute-humidity index for the clear-cut area, the correlation coefficient is increased from +0.62 to +0.76, but the standard error of estimate is increased from ±2.49 percent to ±9.19 percent. Thus an average of 100 observations based upon the curve would have the fairly large standard error of ±0.92 percent.

CORRELATION OF YESTERDAY'S TEMPERATURE AND RELATIVE HUMIDITY WITH TODAY'S DUFF MOISTURE

The fact is well recognized that forest fuels do not respond instantly to sudden changes in the weather. The moisture content of any heavy fuel lags considerably. Since duff is an extremely light and porous material, its moisture content is more closely correlated with atmospheric conditions than that of other forest fuels; but even duff moisture is slower to change than humidity and temperature. A question arises as to whether duff moisture lags enough to justify correlating today's duff-moisture content with yesterday's weather.

The importance of yesterday's temperature and relative humidity as compared with today's in relation to current duff moisture was examined by analyzing the records made on the clear-cut area when the number of days since 0.01 inch of precipitation was 2 or more. In computing the absolute-humidity index different weights were given to the observations taken on the 2 days, respectively. For instance, in one correlation between duff moisture and absolute-humidity index the latter was an average weighted in the ratio of 1 part for yesterday to 3 parts for today. This correlation produced a higher coefficient than any of the other combinations, +0.71; but the improvement in correlation indicated by this coefficient was not large enough to be significant. Hence, it appears that duff moisture on the clear-cut area lags behind the weather but slightly when the number of days since 0.01 inch of precipitation is 2 or more. This restriction on the data has, of course, excluded the influence of most periods of unsettled weather, in other words of most of those days when the greatest lag in duff moisture would be expected.

CORRELATION OF ½-INCH-WOOD MOISTURE AND ABSOLUTE-HUMIDITY INDEX

Two correlations were made between ½-inch-wood moisture and the absolute-humidity index by use of the afternoon measurements taken on the clear-cut area. In the first, all observations made less than 2 days after 0.01 inch of precipitation were rejected. The relation disclosed by this correlation (fig. 11), the regression for which

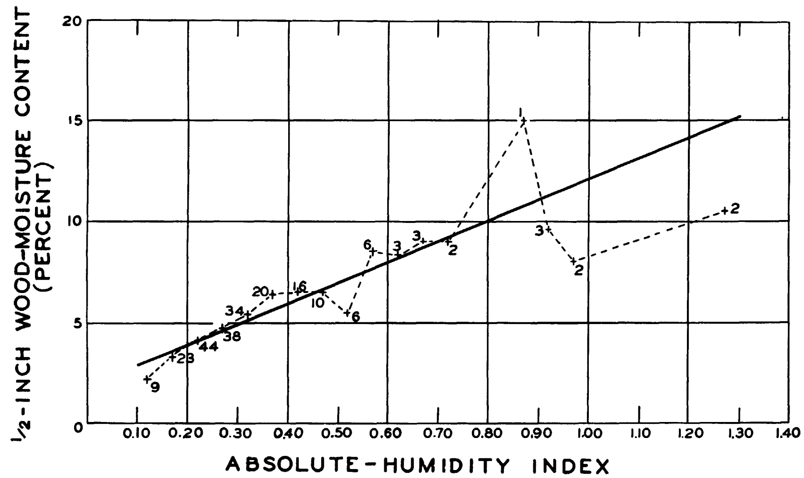

FIGURE 11.—Moisture content of ½-inch wood and absolute-humidity index $\left(\frac{RH}{T}\right)$ on clear-cut area. (Basis, 222 observations taken at 4:30 p. m. 2 or more days after 0.01 inch of precipitation.) A=relative humidity divided by temperature. Y=½-inch-wood moisture content. Correlation coefficient $(r_{Y.A})$= +0.68. Standard error of estimate $(S_{Y.A})=\pm1.87$. Regression equation is $Y=10.27A+1.83$.

is linear, is slightly closer than that brought out by any of the correlations previously made; the correlation coefficient is +0.68, and the standard error of estimate is ±1.87 percent. In the second correlation, use was made of all available afternoon data for the clear-cut area, including those that had been rejected in the first. As will be seen from figure 12, the regression is curvilinear. This is due almost entirely to the influence of precipitation.

An advantage and a disadvantage are associated with use of either of these two correlations for the purpose of estimating ½-inch-wood moisture from the absolute-humidity index. For estimates based on the curvilinear regression the coefficient was exceptionally high, +0.90, but the standard error of estimate was ±7.46. Thus whereas an average of 100 estimates based on the linear regression would have a standard error of only ±0.19, an average of 100 estimates from the curve would have a standard error of ±0.75. The linear regression applies only when the number of days since 0.01 inch of precipitation is at least 2, but the curvilinear regression can be used for all days. There seems to be little choice between the two, since use of the first is restricted and use of the second permits reasonably accurate estimates only if at least 100 observations are averaged.

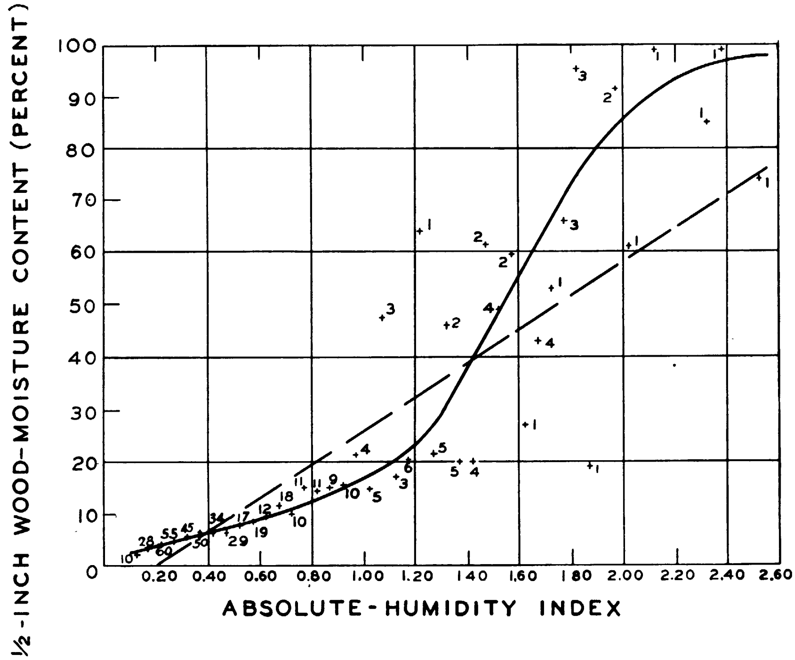

FIGURE 12.—Moisture content of ½-inch wood and absolute-humidity index $\left(\frac{RH}{T}\right)$ on clear-cut area. (Basis, all available afternoon data, 494 observations taken at 4:30 p. m.) For linear regression, correlation coefficient=+0.79, and standard error of estimate=±10.6 percent. For curvilinear regression, correlation coefficient=+0.90 and standard error of estimate=±7.46 percent.

RECOMMENDATIONS FOR FURTHER WORK

The results of this analysis suggest several recommendations for further work.

Although in this study correlation of total air movement during the daytime with the moisture content of lightweight fuels revealed no significant relation, it is possible that a significant relation exists between wind velocity during the hours of rapid drying only, say 9 a. m. to noon, and afternoon fuel moisture. The effect of wind should be further investigated.

It might be well, also, to investigate under northern Rocky Mountain conditions some variables not considered in this analysis, such as solar radiation and soil moisture. Results of a study by Stickel (*10*) indicated a slight correlation between these two factors and duff moisture in the Adirondacks. At present satisfactory methods of measuring these variables are wanting, especially in the case of soil moisture.

Some valuable information might be obtained through study of the correlation between fuel moisture and saturation deficit of the atmosphere; that is, the quantity of water vapor that would have to be added to the atmosphere at a given time in order to produce saturation. This factor provides a measure of the drying power of the atmosphere.

SUMMARY

In efforts toward satisfactory control of the forest fires that do tremendous damage in the United States each year, especially in the northern Rocky Mountain region, forest administrative officers are aided by current knowledge of fire danger—that is, of the sum total of the factors that determine whether fires will start, spread, and do damage. A complete understanding of current fire danger is difficult to obtain, because many factors are involved. By making observations or measurements of several of the most important factors and properly integrating them, however, the forest protectionist can determine the relative fire danger existing at a given time and place. Such a determination guides him in deciding whether and if so how much his force should be temporarily expanded or reduced, and how it should be distributed. In addition, through knowledge of the influence of given factors on fire danger the protectionist is assisted in interpreting weather forecasts and thus in preparing for all classes of fire danger that are likely to arise.

Fuel-moisture content has a very important bearing upon the ease with which fires start and the rate at which they spread. Weather, in turn, is the principal determinant of the moisture content of fuels. Current weather bears an especially close relation to the moisture content of duff and small branch wood, two fuels that are very widely distributed and that carry fire from tree to tree and from log to log. The relation between individual weather elements and the moisture content of these lightweight fuels must be understood before the proper weight can be assigned to each of the many weather factors that contribute to fire danger.

At the Priest River, Idaho, branch of the Northern Rocky Mountain Forest and Range Experiment Station, simultaneous daily measurements have been made, beginning in 1924, of duff-moisture content and the following weather elements and related factors: Maximum, minimum, and current air temperature; temperature of the dew point; current, minimum, and average relative humidity; precipitation, and the number of days since 0.01, 0.10, 0.20, 0.30, and 0.40 inch, respectively, of precipitation; and evaporation. Beginning in 1929, measurements were made also of ½-inch-wood moisture. Wind and maximum duff temperature were added in 1930. These measurements have been made on three adjacent sites in the western white pine type, approximately alike in all respects except that one is clear cut, one-half cut, and one fully timbered.

The fundamental relations between the individual weather elements measured and duff-moisture content for the clear-cut area were examined by means of multiple-correlation analysis. The results of the analysis do not apply to a rainy day or to a day immediately following rain. Data for such days were eliminated to avoid personal errors of fitting freehand curves and to facilitate analysis.

The analysis has definitely shown that of the weather elements and related factors examined current air temperature and relative humidity have the most important effect upon the moisture content of surface duff. Of 14 other weather factors studied, the most important were found to be wind, evaporation, duff temperature, temperature of the dew point, and number of days since 0.01 inch of precipitation. Current air temperature and relative humidity were found to explain all but about 3 percent of the total variance in duff-moisture content associated with those factors and the additional factors just listed. Thus inclusion of the latter in further correlations was impractical.

In this analysis great advantage resulted from the use of the variable $\frac{RH}{T}$, which represents the ratio of relative humidity to air temperature and constitutes an index of absolute humidity. One advantage foreseen in a method of estimating fire danger through use of this variable was that it would make possible fire-danger ratings for the past seasons during which records were made of air temperature and relative humidity but not of duff moisture.

Correlations of duff moisture with relative humidity and air temperature showed errors so large as to preclude all possibility that estimates of duff moisture based on simple measurement of humidity and temperature can be substituted satisfactorily in field practice for actual duff-moisture measurements. Averages for as many as 50 estimates based on these correlations, however, are acceptable for use in rating the severity of a fire season.

Coefficients of correlation of duff moisture with relative humidity and air temperature for the half-cut and full-timbered areas were slightly lower than those for the clear-cut area, and had larger errors associated with them. The usefulness of these correlations is restricted also by the fact that they do not apply until 5 days and 6 days, respectively, after rain.

Coefficients of correlation of ½-inch-wood moisture with relative humidity and air temperature for the three areas differed but little from those of duff moisture.

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