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THE ASSOCIATION BETWEEN ATMOSPHERIC HUMIDITY AND FUEL MOISTURE

by
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ABSTRACT

The state of knowledge of the influence of atmospheric humidity on the moisture content of surface fuels in the open is discussed.

The author's experimental results indicate that prediction of fuel moisture based on atmospheric humidity varies throughout the day and night, that the degree of association between relative humidity and fuel moisture is directly related to the rate of change of the relative humidity, and that relative humidity is a better indicator of fuel moisture than saturation deficit at all times, except possibly during the night.

EXTRAIT

Revue des connaissances actuelles sur l'influence de l'humidité atmosphérique sur la teneur en humidité des matières combustibles formant la litière d'une clairière. Il résulte d'expériences conduites par l'auteur que ni l'humidité relative ni le manque quantitatif ("déficit") de saturation de l'atmosphère constituent une fonction précise et constante des variations globales de la dite teneur. Cependant, sauf la nuit, le taux de variation de l'humidité relative a une influence plus directe que le manque qualitatif de saturation, ce qui lui donne une valeur indicative plus juste.

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INTRODUCTION

Prior to 1923 little was known about the specific influence of the various weather parameters on fire danger, except that rainy weather or cool days with high humidity reduced, while hot and dry weather increased, the flammability of fuels (Gisborne, 1928). The seasonal and diurnal fluctuations of fire danger were known in a gross manner, but beyond some theoretical explanations (Hoffman and Osborne, 1923; Show and Kotok, 1924) little experimentally substantiated information was available on how and why various weather elements exaggerate or alleviate fire danger.

The wealth of information on fuel moisture[2]-weather relations began to accumulate between the late 1920's and 1940's, when the results of several long term and independent studies were published in Canada and the United States (Gisborne, 1928; Nichols, 1928, 1929, 1930; Gast, 1929; Wright, 1930, 1932; Simpson, 1930; Stickel, 1931; Jemison, 1935; Byram, 1940; Hayes, 1941; Byram and Jemison, 1943; Beall, 1947; Macleod, 1948). The dependence of flammability on the moisture content of fuels was recognized and described quantitatively (Gisborne, 1928, Wright, 1930), and the weaknesses of using any one of the numerous weather parameters by itself to express fuel moisture-weather relations were conclusively demonstrated (Stickel, 1931).

Evaporation from Livingston atmometers (Wright, 1930; Stickel, 1931), from evaporation pans (Beall, 1934), indications of the duff hygrometer (Gisborne, 1928), the moisture content of hazard sticks (Gisborne, 1933; Matthews, 1935), match splints (Beall, 1947), and thin wooden slats

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[2] Unless qualified, fuel moisture as used in this paper means the moisture contained in light surface forest fuels, such as twigs, fallen needles and leaves, and dead herbaceous vegetation.

(Matthews, 1935; Nelson, 1963), were found to correlate remarkably well with fuel flammability, and various fire danger rating systems were devised to express the relationship for operational use (Wright, 1933; Gisborne, 1936; Beall, 1948; Villeneuve, 1948; Jemison, Lindenmuth and Keetch, 1949; Nelson, 1955, 1964).

During the 1950's, methods of fire control and the practice of prescribed burning made great technological advances (Davis, 1959), and the increasing demand for a more accurate fire danger rating system prompted further investigations into the problems of fuel moisture-weather relations (Wilson, 1958; King, 1958; Franssila, 1958; McArthur, 1962; Schalk, 1962; King and Linton, 1963; Steen, 1963; Nelson, 1963; Williams, 1964; Muraro, 1964; Storey, 1965).

The accuracy of the danger estimates ultimately rests on the validity of the assumed fuel moisture-weather relationships. To improve upon the systems, the information pertaining to fuel moisture-weather relations needs to be assembled, critically re-examined and complemented.

This paper examines the association between atmospheric humidity at 1.35 m. height and fuel moisture content in the open. It is assumed that while no causal relation exists between these two parameters, they may vary together owing to influences common to both.

THE INFLUENCE OF ATMOSPHERIC HUMIDITY

Atmospheric humidity has attracted by far the most attention since the early 1920's. A variety of methods have been employed in the study of fuel moisture-humidity relations. Fuel moisture was measured, or estimated, with duff hygrometers placed about 1-1.5 cm. beneath the surface of forest litter by Gisborne (1928), Wright (1930, 1932), Stickel (1931), and Jemison (1935), or with wooden cylinders and sticks supported about 15 cm. above the ground, in the open by Storey (1965) and in the forest by Franssila (1958), or exposed in an instrument shelter 2 m. above the ground in the open by Schalk (1962). Storey (1965) exposed thin wooden slats as well about 15 cm. above the ground in the open, while Beall (1947) and Macleod (1948) used untreated white pine match splints placed on trays on the ground in forest stands. Some investigators sampled a great variety of forest fuels, held them in trays just above the ground (Hoffman and Osborne, 1923; Wright, 1930; Steen, 1963), or suspended the samples in wire baskets at a height of 1.35 m. (Simpson, 1930).

The times at which fuel moisture and relative humidity measurements were made varied, although all the published records, with one exception, relate only to daytime measurements. Some investigators attempted to gather information under all kinds of weather conditions throughout the day (Gisborne, 1928; Simpson, 1930). Others made periodical measurements at certain times each day (Wright, 1930, 1932; Stickel, 1931; Jemison, 1935; Macleod, 1948; Schalk, 1962; Storey, 1965). Hoffman and

Osborne (1923), preliminary results, and my own measurements (Figure 1) are the only published results known to me in which continuous measurements of fuel moisture content are reported for a 24-hour or longer period.

Stickel (1931) showed that the normal diurnal cycle of relative humidity can be divided into four periods. Slow changes in humidity characterize the night and early afternoon periods, while in the morning and evening transitional periods rates of change are five to six times greater. By correlating duff moisture with relative humidity and with dew-point depression, then analyzing the pairs of observations obtained at 11 a.m., 2 p.m. and 5 p.m. on more than 2,000 occasions, Stickel conclusively demonstrated that the effect of atmospheric humidity on predictions of duff moisture is not the same during the morning transitional, the afternoon, and the evening transitional periods. Also, by comparing alienation indexes, he showed that the depression of dew point is a slightly better indicator of duff moisture content than relative humidity. The latter finding, however, has little support, for none of his correlations could account for more than 23 percent of the total variation of duff moisture. The most plausible explanation for his weak correlations is that he did not treat the data gathered on rainy days separately from those obtained on rainless days.

By separating his observations obtained on days that had no precipitation for at least 24 hours prior to the reading from those obtained on rainy days, Jemison (1935) drew attention to the importance of the immediately preceding weather. The rejection of the high values of duff moisture that resulted from rain within the preceding 24-hour period, though Jemison did not mention it, actually implied that fast-reacting surface fuels need a maximum of 24 hours without precipitation before their normal diurnal cycle of gain and loss is established. That cycle would, under most circumstances, coincide with the diurnal cycle of the relative humidity. His coefficient of determination for a total of 226 pairs of relative humidity and duff moisture observations, made at 4:30 p.m., was a significantly high 45.2 percent.

Two important deductions can be made from these early investigations: (1) The degree of association between atmospheric humidity and fuel moisture is affected by precipitation for a maximum period of 24 hours following the cessation of rain; (2) When used for predicting fuel moisture, the effect of atmospheric humidity is not constant throughout the day.

The evidence for either deduction is very sparse. The first one has apparently been accepted intuitively after Jemison (1935), for most of the investigators in later years simply rejected their fuel moisture data from rainy days without attempting to compare them with those unaffected by rain (Macleod, 1948; McArthur, 1962; Steen, 1963; Storey, 1965). Franssila (1958) was one who compared field measurements from rainy days with those from rainless days. He demonstrated a strong correlation between fuel moisture under *Pinus silvestris* stands and relative humidity 15 cm. above the litter for rainless days (see his Figure 3), and a very weak correlation on days with 1 mm. or more precipitation. From his data I calculated the correlation coefficients, .8894 and .1003, respectively.

To support the second deduction, that the efficacy of atmospheric humidity in predicting fuel moisture varies throughout the day, I have found only two sources of indirect evidence. Simpson (1930) remarked that when relative humidity is used for estimating fuel moisture, "the greatest errors were found to occur when the estimates were based on high humidity values such as often occur at night" (p.374). This statement implies that correlations based on night-time observations would yield smaller coefficients of determination than those based on daytime measurements. Macleod (1948) agreed with this, stating that "minor variations in nocturnal relative humidity have a very small effect on fuel moistures" (p.13).

Recent publications concerning the effect of atmospheric humidity on fuel moisture changes present no further information concerning the validity of the two deductions. Steen (1963), through a visual examination of his results, concluded that there was a close association between relative humidity, as measured at 15 cm. height from 6 a.m. through 10 p.m., and the moisture content of five different kinds of fuels and also that the association "appeared to be more consistent in the afternoon than in the morning" (p.3). From 2 p.m. observations of relative humidity, and the depression of wet bulb temperature at 2 p.m., both measured at a 1.35 m. height in an instrument shelter, and from the moisture content of 3 mm. thin basswood slats supported 15 cm. above the ground in the open, Storey (1965) computed statistically significant correlations, with coefficients of determination 67.7 percent and 65.8 percent, respectively. Both Steen and Storey used observations obtained only on rainless days.

Wilson (1958) suggested that the moisture loss from light fuels is a function of the difference between the saturation vapour pressure of the atmosphere surrounding the fuel. King (1958) observed that both atmospheric saturation deficit and wind control the constant drying rate of surface fuels until a critical fuel moisture is reached. Below this point the atmospheric saturation deficit is the main controlling factor while wind has no direct influence on the drying of fuels. He also felt that the drying rate of fuels is a function of the fuel temperature and of the vapour pressure of the atmosphere. Neither author presented field measurements to substantiate his suggestions.

Schalk (1962) thought that the initial moisture content of small wood samples affects the amount of moisture they lose in a given time interval. To test the hypothesis he placed several 1.5 x 1.5 x 25 cm. *Pinus silvestris* wood samples in a Stevenson screen in the open, and measured their weights at 8:30 a.m., 11:30 a.m., 2:30 p.m. and 5:30 p.m., regularly for four weeks. Simultaneously, he recorded relative humidity and air temperature in an adjacent screen. From those records he correlated the loss of weight of the samples and the average saturation deficit for each three-hour period. The average saturation deficit could account for only 23 percent of the total variations in the loss of sample weight. He then weighted each observation of sample-weight loss by the absolute amount of moisture the sample contained at the beginning of each period, and correlated the results with the corresponding average saturation deficit. The coefficient of determination improved significantly to 64 percent, indicating that the initial moisture content had a significant effect on the relationship between moisture loss and saturation deficit. It is important to note that during the experiment the highest moisture content of the samples was 8 percent below the fibre saturation point, and that the samples were shielded from precipitation as well as radiation. His results substantiate Leroy's (1954) finding that, below the fibre saturation point, the amount of energy required to overcome the force of water retention increases exponentially, and inversely with the amount of water remaining. Also, they indirectly support the idea that initial moisture content is an important parameter in the calculation of current moisture content as incorporated in the Canadian forest fire danger tables (Anon., 1965).

EXPERIMENTAL RESULTS

Several observations and conclusions emerge from the literature concerning the relationship between fuel moisture and atmospheric humidity. Some of the evidence is contradictory, or inadequately substantiated, and the establishment of a unified theory, or of a relationship of general validity, requires further experimentation. The greatest obstacle lies in the vast diversity of the methods of measurement and of the presentation and analysis of results employed by the investigators.

From the practical standpoint of predicting fuel moisture, three questions are of interest:

(a) Can the changes in fuel moisture be accounted for by the changes of relative humidity or saturation deficit?

(b) Which one of the two most commonly used expressions of atmospheric humidity is a better indicator of fuel moisture changes?

(c) Does the efficacy of either relative humidity or saturation deficit in predicting fuel moisture remain constant at all times, and under a variety of weather conditions?

To accept a positive answer for (a), a coefficient of determination of 0.75 is necessary. To leave 25 percent of the variations in fuel moisture unexplained is a necessary compromise, for the complexity of the fuel moisture-weather relations cannot be expected to yield a better coefficient of determination for any one weather element alone in the uncontrolled natural environment. The answers for (b) and (c) can be obtained from a statistical analysis of the coefficients of determination. To answer these questions I designed and carried out an experiment during July, August, and the first part of September, 1966.

The use of natural surface fuels, and the method of destructive sampling, were rejected to gain in precision, reproducibility, and physical exactness. None of the three most widely used artificial fuels appeared acceptable as a standard. Untreated match splints (Beall, 1947) have a tendency to trap excess moisture. Shifting in the tray disrupts the drying-regime curves, and splint losses due to animal activity have occasionally been noted. Pre-weathered thin basswood slats and pine dowels (Storey, 1965) are too slow to respond to the changes of weather elements (*op. cit.* p.4) compared with the light surface fuels.

Kiln-dried western white pine (*Pinus monticola* Dougl.) sapwood of 0.40 specific gravity (Anon., 1951, oven dry weight basis) was selected. Thirty-nine slats, each measuring 25.40 x 0.64 x 0.25 cm. (10 x 1/4 x 1/10 in.) were stapled to two slats of 37.78 x 0.64 x 0.25 cm. (14.875 x 1/4 x 1/10 in.) with a space of 0.32 cm. (1/8 in.) between each slat. The total surface area of the sample was 1,853 cm.^{2}; its total volume was 172 cm.^{3}.

Fast-drying surface fuels in nature are characterized by an almost infinite ratio of the surface area surrounded by air to that in contact with solids. To approximate the natural ventilating conditions, the samples were placed on wire frames 2.5 cm. above a standardized fuel bed[3] at a climatological station. Before exposure, each sample was immersed in water for one hour to bring the moisture content of its outermost woodlayer above fibre saturation. Then the sample was placed on wire frames for two weeks of weathering with its long axis oriented true east-west. Previous experience with the samples indicated that the weight loss from weathering becomes asymptotic in about ten days. Every Monday morning the three-week-old sample was removed for oven drying and replaced by a new sample. At any one time, past the initial two weeks of the experiment, there were three samples on the fuel bed, a new, a one-week-old, and a two-week-old one, respectively. Each day the sample in its third week of exposure was weighed to ±0.05 g. accuracy, once every hour between 0200 and 2200 hrs., and every 30 minutes around sunrise and for two hours before sunset. It was also weighed immediately after any rain.

After the determination of oven-dry weight the sample was discarded. The moisture content of each sample was calculated from hourly or half-hourly measurements on the basis of its oven-dry weight. Simultaneously with the weighing of the sample, relative humidity and air temperature were continuously recorded with two hygrothermographs, one in a Stevenson screen and the other in a plastic screen, both screens at 1.35 m. above the

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[3] The construction of a standardized fuel bed: at a climatological station in the open, remove grass and top soil from a 60 cm. x 120 cm. (2 ft. x 4 ft.) area with its long axis running north-south. Cover the bottom with 2.5 cm. (1 in.) of pea gravel, fill in 5 cm. (2 in.) with fine sand, and place a 5 cm. (2 in.) layer of compacted and at least one-year-old fallen pine needles on top. The top surface of the fuel bed should be flush with the height of the surrounding closely cut grass. It is important to encircle the fuel bed with a good turf, as rain could splash mud and dirt on the fuel samples. Sink iron angles at close intervals along the path leading to the fuel bed to prevent the observers from walking on the grass.

ground. The hygrothermographs were calibrated at 12°, 32°, 50°, 70°, 80°F; 25%, 40%, 65%, 80%, 96%, before the experiment, in constant temperature and humidity rooms. They were rechecked at the end of the experiment. The accuracy of temperature and relative humidity records were ±0.5°F and ±3%, respectively. Every Monday the hygrothermograph hairs were washed with distilled water or rainwater, and were adjusted to indicate 96 percent when thoroughly moist. The temperature records were checked further with certified mercury-in-glass standard and minimum-maximum thermometers. Precipitation was recorded by a syphon-type recording rain gauge with an accuracy of 0.2 mm. (0.01 in.); traces of rain at the site were noted in the observer's book. The duration of sunshine was recorded with a Jordan sunshine recorder, and the flux density of the short-wave radiation with a bimetallic actinograph equipped with a 1/24 hour revolution drum (time lag of two minutes). The experiment was terminated after the first frost of over two hours duration at screen level in early September.

The eight weeks' records of fuel moisture and weather measurements were scrutinized for errors and for necessary corrections. Data from sample no. 7 had to be eliminated. This sample was originally placed on the fuel bed in its soaked condition after 1 p.m. on a clear day with continuous and intense solar radiation, and with high afternoon air temperatures. The fast rate of drying seems to have caused the case-hardening that prevented the sample from losing about 4-6 g. of trapped water. This resulted in sample no. 7 giving fuel moisture values 8 to 10 percent higher than those for sample nos. 6 and 8.

For the statistical analysis, all records obtained at least 24 hours after a trace of rain were separated (A), then divided into four periods (Table 1): night period A1 (11 p.m. - 5:30 a.m.), morning transitional period A3 (6 a.m. - 12 noon), afternoon period A2 (12:30 p.m. - 4 p.m.), and the evening transitional period A4 (4:30 p.m. - 10 p.m.). Those obtained during the 24 hours immediately following precipitation were classified according to the presence (B1) or absence (B2) of solar radiation. An unbroken radiation trace of 30 minutes duration before each weighing qualified the fuel moisture observation for class B1.

Simultaneous records of relative humidity and of fuel moisture were correlated (Table 1, columns a). The coefficients of determination were computed according to the various weather and time period classes for each sample and for the total of all the samples in each class. Saturation deficit values were computed from the temperature and relative humidity records, and were treated similarly to the relative humidity (Table 1, columns b).

Table 1 reveals that neither relative humidity nor the saturation deficit of the atmosphere can explain the total variation of moisture content with constant precision.

Relative humidity accounted for a significantly greater portion of the moisture content variations than saturation deficit during all but the rainless night and afternoon periods. Its usefulness for predicting

TABLE 1. COEFFICIENT OF DETERMINATION X 100. EXPRESSES THE PERCENTAGE OF THE TOTAL VARIATION OF THE SAMPLE MOISTURE CONTENT THAT COINCIDES WITH THE TOTAL VARIATION OF RELATIVE HUMIDITY (a), OR SATURATION DEFICIT (b).

SAMPLE	A1		A2		A3		A4		B1		B2	
No.	a[1]	b[2]	a	b	a	b	a	b	a	b	a	b
1001	39***[3]	46***	69***	78***	75***	75***	85***	59***	59***	35*	58***	53***
1002	9	4	3	37**	86***	81***	93***	29*	73***	70***	59***	58***
1003	60**	84***	78***	42**	85***	74***	54*	71**	72***	64***	74***	51***
1004	0	0	22	41	94***	95***	94*	--	60**	44*	61***	68***
1005	20**	25***	65***	56***	93***	82***	85***	85***	--	--	--	--
1006	40*	53***	89***	89***	96***	87***	94***	79***	--	--	84***	76***
1008	42*	43*	71***	55***	80***	73***	68***	59***	75***	72***	31***	27***
SAMPLES COMBINED	29***	33***	66***	67***	84***	76***	75***	58***	63***	60***	54***	51***

[1] The two variables correlated are: relative humidity in Stevenson screen (%), and the moisture content of standardized fine surface fuel (% of oven-dry weight).

[2] The two variables correlated are: saturation deficit in Stevenson screen (mb.), and the moisture content of fuels same as in footnote 1.

[3] Asterisks: *** significant at 0.001 probability
** significant at 0.01 probability
* significant at 0.05 probability

moisture content seems to be directly related to its rate of change, being highest during the morning transitional period and lowest at night under stable conditions with temperature inversion. During periods immediately following precipitation, up to 24 hours after cessation of rain, the same relation appears to hold. With solar radiation (Table 1, column B1, a), the rate of change of relative humidity and its effect on predictions are greater than without solar radiation (Table 1, column B2, a).

For fuel-moisture-estimating purposes, relative humidity seems to be reliable only during the morning and evening transitional periods. For all other periods the coefficients of determination were significantly less than 0.75, which means that more than 25 percent of the total variation of moisture content was due to factors other than those influencing the variation of relative humidity.

The variation that occurred in results when saturation deficit was used for predicting did not coincide with the variation in its rate of change. Although the coefficient of determination was the highest during the morning transitional period, when the rate of change of the saturation deficit is the greatest, the second highest value was not obtained for the evening transitional period. It occurred in the afternoon period under conditions of convective instability and strong temperature-lapse rates near the ground. At night, and for some of the samples during the afternoon period, a better correlation between the changes of fuel moisture and changes of saturation deficit was obtained than between changes of fuel moisture and changes of relative humidity (Table 1, columns A1, b, and A1, a). However, the differences are of very little practical significance because more than 65 percent of the moisture content changes are unexplained.

Most of the coefficients of determination throughout Table 1 are significant at the 99.9 percent level. This can be misleading because the number of pairs of observations (Table 2) can alter the significance of the coefficient of determination at various probabilities.

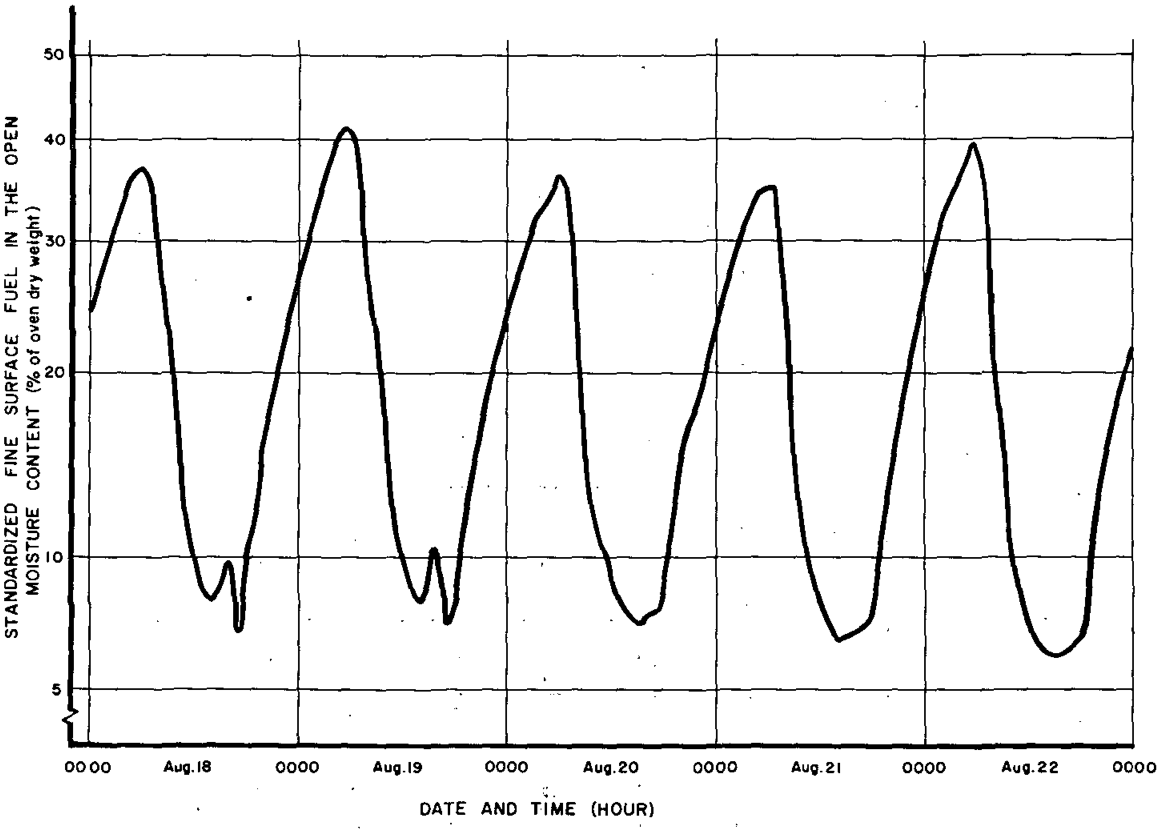
There are 93 pairs of observations when all observations from the seven samples are combined for all the different periods under two categories of weather (Table 2, last row, in column B1, b). With 93 pairs of observations the coefficient of determination need not exceed 11 percent to be significant at 0.001 probability. When its value drops to a negligible 4 percent, it is still significant at the 95 percent level. Conversely, the lowest number of pairs of observation is 4 for sample no. 1004 (Table 2, column A4, a). With such a low number of observations the coefficient of determination must exceed 99.5 percent to reach the 99.9 percent level of significance. Even for a 95 percent level of significance, its value would have to reach 90 percent. All the coefficients (Tables 1 and 2) of determination appear statistically acceptable. Where they are less than 99.9 percent significant, or not significant at all, the lack of statistical significance is caused more by the exceptionally low number of observations than by the weakness of the correlations.

TABLE 2. NUMBER OF PAIRS OF OBSERVATIONS ON WHICH THE CORRELATION IS BASED BETWEEN RELATIVE HUMIDITY IN STEVENSON SCREEN (a), OR SATURATION DEFICIT IN STEVENSON SCREEN (b), AND THE MOISTURE CONTENT OF STANDARDIZED FINE SURFACE FUELS IN THE OPEN. JULY, AUGUST, SEPTEMBER, 1966.

SAMPLE	A1		A2		A3		A4		B1		B2	
No.	a	b	a	b	a	b	a	b	a	b	a	b
1001	48	48	60	60	70	70	33	33	18	17	107	106
1002	24	24	23	22	35	35	19	19	16	15	78	77
1003	12	12	16	16	23	23	10	10	19	17	95	92
1004	6	6	8	8	9	9	4	-	11	11	66	62
1005	37	37	60	59	62	62	32	32	-	-	-	-
1006	20	20	39	39	38	38	16	16	-	-	25	23
1008	12	11	45	46	36	36	20	18	36	33	130	122
SAMPLES COMBINED	159	158	251	250	273	273	134	128	100	93	501	482

The lack of agreement between the number of pairs of observations used in correlations a and b (Table 2) is due to the omission of those pairs of observations, nearly always from correlation b, where the temperature records were missing and the saturation deficit values could not be computed. This discrepancy had no discernible influence on either the coefficients of determination or the significance of their values, and its effect on the mean moisture content values was negligible (Table 3).

To further illustrate the low coefficient of determination in Table 1, column A1, a, hourly measurements of relative humidity and air temperature are given in Table 4 for days whose moisture-content curve is reproduced in Figure 1. Table 4 and Figure 1 show that at night, while the moisture content increases, until shortly before 6 a.m., the range of relative humidities is negligible (4 to 6 percent) between midnight and 6 a.m. Thus, only a weak correlation can be expected. Moreover, there is no correlation between the maximum overnight relative humidity and the



igure 1. Moisture content of the fine surface fuel sample exposed 2.5 cm.
bove a standardized pine needle fuel bed in the open, on five consecutive
lear, rainless days in 1966. Measurements are hourly, or half hourly
round maximum and minimum points. Time is marked on the abscissa at mid-
ight on each day.

TABLE 3. MEAN VALUES OF STANDARDIZED FINE SURFACE FUEL MOISTURE CONTENTS CALCULATED FROM THE OBSERVATIONS USED IN THE CORRELATION STUDY. PERCENTAGE OF OVEN-DRY WEIGHT.

SAMPLE	A1		A2		A3		A4		B1		B2	
No.	a	b	a	b	a	b	a	b	a	b	a	b
1001	30.2	30.2	8.1	8.1	19.5	19.4	11.3	11.3	16.6	16.6	46.2	45.8
1002	28.1	28.1	9.6	9.6	21.7	21.7	13.6	13.6	20.8	21.2	24.3	24.2
1003	30.1	30.1	8.5	8.5	21.0	21.0	12.9	12.9	24.8	25.6	31.8	31.6
1004	31.0	31.0	12.3	12.3	25.3	25.3	18.6	-	25.3	25.3	45.1	45.6
1005	31.9	31.9	9.2	9.4	24.4	24.4	13.8	13.8	-	-	-	-
1006	29.3	29.3	7.4	7.4	20.8	20.8	12.3	12.3	-	-	64.8	63.7
1008	30.4	30.8	13.8	14.2	24.4	24.4	20.5	21.0	22.3	21.5	39.6	39.2
SAMPLES COMBINED	30.2	30.3	9.6	9.7	22.1	21.9	14.0	13.9	21.8	21.8	39.1	38.8

TABLE 4. RELATIVE HUMIDITY (R.H. %) AND AIR TEMPERATURE (T.°F) MEASURED IN THE STEVENSON SCREEN DURING FIVE CLEAR DAYS IN AUGUST 1966.

Hour (P.S.T.)	Aug. 18		Aug. 19		Aug. 20		Aug. 21		Aug. 22	
	R.H.	T.	R.H.	T.	R.H.	T.	R.H.	T.	R.H.	T.
0000	92	42	88	40	92	40	86	43	90	47
0100	91	40	92	39	93	38	89	42	94	45
0200	90	38	90	37	96	36	90	40	93	44
0300	91	37	91	37	96	35	90	39	94	43
0400	92	38	89	37	96	34	91	38	92	42
0500	89	40	91	37	93	34	92	37	92	40
0600	88	41	92	38	95	35	90	38	96	41
0700	88	42	89	43	89	41	84	44	82	47
0800	87	42	74	47	64	51	66	52	62	55
0900	74	47	53	57	45	58	43	63	49	63
1000	64	51	50	61	43	61	34	67	41	67
1100	50	57	37	64	40	65	32	70	37	71
1200	40	61	34	66	38	67	29	74	31	75
1300	33	63	33	66	32	68	24	76	28	77
1400	31	66	32	69	27	71	21	78	27	79
1500	44	59	28	70	27	72	22	78	26	81
1600	43	61	24	71	28	73	21	78	23	81
1700	37	63	26	70	28	73	20	78	23	81
1800	38	62	27	69	30	71	26	75	27	78
1900	58	55	57	57	59	61	54	67	55	64
2000	75	49	74	51	73	54	65	59	69	57
2100	83	46	86	46	84	49	81	53	73	53
2200	86	43	85	44	89	47	85	50	77	51
2300	88	41	90	42	82	45	88	49	82	49
2400	88	40	92	40	86	43	90	47	90	46

maximum moisture content reached in the early morning. This evidence suggests that, while the high relative humidities may be a necessary requirement for the fuels to gain moisture at night, when no precipitation occurs, a factor or a combination of factors other than relative humidity and saturation deficit determines both the rate of change of moisture content and its maximum value in the early morning.

DISCUSSION AND CONCLUSIONS

The choice of using correlation techniques as opposed to the methods of regression emphasizes two points. First, the two variables, i.e. atmospheric humidity at screen height and fuel moisture, cannot be considered as independent and dependent. Secondly, the change of atmospheric humidity does not bring about a change in fuel moisture, but atmospheric humidity and fuel moisture vary together owing to influences common to both. An empirical regression equation to determine how much humidity change is required for a certain change in fuel moisture would be of little value. Schalk (1962) wrote, "The usefulness of drawing up isopleth charts, giving the expected moisture content according to point of time and region, is probably limited to reproducing a condition that is seldom attained. It [is] more desirable to trace the true variations and to ascertain the causes" (p.16).

The segregation of the humidity and fuel moisture measurements into those obtained immediately after rain, and those taken at least 24 hours after the cessation of rain, implies that the degree of association between atmospheric humidity and fuel moisture is not expected to be identical under the two conditions. In the absence of rain, surface fuels gain moisture during the period from shortly before sunset to sunrise, and lose moisture during the day (Figure 1). Relative humidity approximates a similar diurnal cycle. Immediately after precipitation, fuels begin to lose moisture, regardless of the time of the day or night, and the water loss continues until external or internal factors become limiting and reverse the condition. How the relative humidity changes after the rain, however, is a function of the time of day. After an initial temporary decrease, it may begin to increase in the absence of solar radiation. If the sky remains overcast, the relative humidity may stay high for a considerable period; when the sky is clear and there is solar radiation, it drops sharply. Taking into consideration all possible combinations of the trends of fuel moisture and relative humidity following rain, and the times at which precipitation may stop, a minimum of 24 hours is needed before the phase angle between the fuel moisture and relative humidity cycles becomes zero.

In dividing the rainless days into four periods, I have followed Stickel (1931) closely. The differentiation of the transitional periods from the afternoon and night periods is an essential feature of the analysis because the former are the periods when the fuel moisture and relative humidity cycles appear to be in phase. Apart from the pragmatic implications of pointing out those periods when the association is close, the analysis draws attention to other weather elements, particularly to radiant solar heat, which is likely to operate during the morning and early evening.

The degree of association between relative humidity and fuel moisture was found to be directly related to the rate of change of the relative humidity. This indicates that there is no direct causal relation between atmospheric humidity at screen level and fuel moisture in nature, and that both variables are under the influence of a weather element, or a combination of weather elements. This is further substantiated by the finding that saturation deficit is always less closely associated with fuel moisture, with the possible exception of the night period.

The following conclusions can be drawn from the results:

(1) The degree of association between fine surface-fuel moisture in the open and the two most commonly used expressions of atmospheric humidity (relative humidity and saturation deficit) displays a great deal of variation at different times of the day and night.

(2) During all periods, with the possible exception of the night period, the use of relative humidity to predict fuel moisture is significantly more accurate than the use of saturation deficit.

(3) The morning transitional period, at least 24 hours after the cessation of rain, seems to be the only time when the association between relative humidity at screen level and fuel moisture is acceptable for the pragmatic purposes of prediction.

REFERENCES

Anon., 1951. Canadian woods, their properties and uses. (2nd ed.) Dept. Resources and Development, For. Br., For. Prod. Lab. Div. King's Printer, Ottawa, Canada.

Anon., 1965. Forest fire danger tables - British Columbia, Coast; British Columbia, Cariboo. Canada, Dept. of Forestry, Publ. 1099, 1101.

Beall, H.W. 1934. Diurnal and seasonal fluctuation of fire hazard in pine forests. For. Chron. X:209-224.

Beall, H.W. 1947. Research in the measurement of forest fire danger. Canada, Dept. Mines and Resources, Dom. For. Serv.

Beall, H.W. 1948. Forest fire danger tables (2nd ed.). Canada, Dept. Mines and Resources, Dom. For. Serv., For. Fire Res. Note 12.

Byram, G.M. 1940. Sun and wind and fuel moisture. J. For. 38 (8): 639-640.

Byram, G.M. and G.M. Jemison. 1943. Solar radiation and forest fuel moisture. J. Agr. Res. 67 (4):149-176.

Davis, K.P. 1959. Forest fire control and use. McGraw Hill Book Co., Inc., New York. 584 pp.

Franssila, M. 1958. Kulovaaran ja Säätekijöiden Välisestä Riippuvuudesta (The dependence of forest fire danger on meteorological factors). Acta For. Fennica 67.

Gast, P.R. 1929. A correlation between solar radiation intensities and relative humidities. U.S. Mo. Weath. Rev. 57:464-465.

Gisborne, H.T. 1928. Measuring forest-fire danger in northern Idaho. U.S.D.A., Misc. Publ. 29. 63 pp.

Gisborne, H.T. 1933. The wood cylinder method of measuring forest inflammability. J. For. 31:673-679.

Gisborne, H.T. 1936. Measuring fire weather and forest inflammability. U.S.D.A., Circular 398. 59 pp.

Hayes, G.L. 1941. Influence of altitude and aspect on daily variations in factors of forest-fire danger. U.S.D.A. Circular 591. 38 pp.

Hoffman, J.V. and Wm. B. Osborne, Jr. 1923. Relative humidity and forest fires. U.S.D.A. For. Serv.

Jemison, G.M. 1935. Influence of weather factors on moisture content of light fuels in forests of the northern Rocky Mountains. J. Agr. Res. 51 (10):885-906.

Jemison, G.M., A.W. Lindenmuth and J.J. Keetch. 1949. Forest fire danger measurement in the eastern United States. Agric. Handbook No. 1, U.S.D.A. For. Serv.

King, A. 1958. In: Proc. of the Fire Weather Conf. (L.J. Dwyer, ed.). Melbourne, July 1958. Commonwealth of Australia, Bur. Meteorol.

King, A.R. and M. Linton. 1963. Moisture variation in forest fuels: the rate of response to climatic changes. Australian J. Appl. Sci. 14 (1):38-49.

Leroy, R. 1954. Une methode correcte de dosage de l'eau (A correct method of expressing moisture content). Chimie Analytique 36 (11):294-301. Commonwealth of Australia C.S.I.R.O. Translation 4092.

McArthur, A.G. 1962. Control burning in Eucalypt forests. Commonwealth of Australia, For. and Timber Bur., Leaflet 80. 31 pp.

Macleod, J.C. 1948. The effect of night weather on forest fire danger. Canada, Dept. of Mines and Resources, Dom. For. Serv., For. Fire Res. Note 14. 29 pp.

Matthews, D.N. 1935. Experience with hazard indicator sticks. J. For. 33:392-397.

Muraro, S.J. 1964. Some effects of slope on fire climate. Canada, Dept. of Forestry, Publ. 1089.

Nelson, R.M. 1955. How to measure forest fire danger in the southeast. Station Paper 52, Southeastern For. Expt. Sta., For. Serv., U.S.D.A.

Nelson, R.M. 1964. The National Fire Danger Rating System: derivation of spread index for eastern and southern States. U.S. For. Serv. Res. Paper SE-13. 44 pp.

Nelson, R.M. Jr. 1963. The hygroscopicity of wood at high temperatures and relative humidities. Master's thesis, North Carolina State College, Raleigh, U.S.A.

Nichols, L.H. 1928. Report to the Quebec Forest Industries Association Ltd., on meteorological and forest fire hazard conditions in the Province of Quebec. Quebec, Canada. 39 pp.

Nichols, L.H. 1929. Second report to the Quebec Forest Industries Association, Ltd., on meteorological and forest fire hazard conditions in the Province of Quebec. Quebec, Canada. 56 pp.

Nichols, L.H. 1930. Third report to the Quebec Forest Industries Association, Ltd., on meteorological and forest fire hazard conditions in the Province of Quebec. Quebec, Canada. 49 pp.

Schalk, J. 1962. Schommelingen in het Vochtgehalte van luchtdroog Hout en hun Samenhang met de atmosferische Omstandigheden (Variations in the moisture content of air-dry wood in relation to atmospheric conditions). Mededelingen van het Lab. voor Houttech., Rijkslandbouwhogeschool, Ghent. No. 16, 20 pp. Commonwealth of Australia, C.S.I.R.O. Translation 6498.

Show, S.B. and E.J. Kotok. 1924. The role of fire in the California pine forests. U.S.D.A. Bull. 1294. 80 pp.

Simpson, A.G. 1930. Relative humidity and short-time fluctuation in the moisture content of forest fuels. U.S. Mo. Weath. Rev. 58:373-374.

Steen, H.K. 1963. Relation between moisture content of fine fuels and relative humidity. U.S. For. Serv., Res. Note PNW-4. 6 pp.

Stickel, P.W. 1931. The measurement and interpretation of forest fire-weather in the western Adirondacks. The New York State Coll. of For., Bull. 4 (3-a). 115 pp.

Storey, T.G. 1965. Estimating the fuel moisture content of indicator sticks from selected weather variables. U.S. For. Serv., Res. Paper PSW-26. 14 pp.

Villeneuve, G.O. 1948. Méthode d'évaluation des dangers d'incendie forestier dans la province de Québec. Ministère des Terres et Forêts, Québec. Bull. 7.

Williams, D.E. 1964. The influence of insolation on fire hazard in coastal Douglas-fir slash. Canada, Dept. of Forestry, Publ. 1060.

Wilson, G.U. 1958. Some problems of estimating and predicting the moisture content of forest and grass fuels. In: Proc. of the Fire Weather Conf., Melbourne, July 1958. Commonwealth of Australia, Bur. Meteorol. pp. 138-146.

Wright, J.G. 1930. The influence of weather on the inflammability of forest fire fuels. Canada, Dept. of the Interior, For. Serv.

Wright, J.G. 1932. Forest fire hazard research as developed and conducted at the Petawawa For. Expt. Sta. Canada, Dept. of the Interior, For. Serv., Div. For. Protection.

Wright, J.G. 1933. Forest fire hazard tables for mixed red and white pine forests, eastern Ontario and western Quebec regions. Canada, Dept. of the Interior, For. Serv., Div. For. Protection.

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