THE MOISTURE CONTENT OF FOREST FUELS - III MOISTURE CONTENT VARIATIONS OF FAST RESPONDING FUELS BELOW THE FIBRE SATURATION POINT

by

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Addendum To

The Moisture Content of Forest Fuels - III

Moisture Content Variations of Fast

Responding Fuels Below the Fiber

Saturation Point

by

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Errata: Page 21

The second last sentence of the first paragraph

This is discussed in some detail in the section on slow responding fuels.

should read

This is discussed in greater detail in Appendix II.

Appendix II

Effect of Day Length on Fuel Moisture

It was pointed out in the main body of the paper that day length was correlated with fuel moisture. The purpose of this appendix is to present a theoretical argument supporting the validity of the correlation.

Assume that on two different days, identical values of temperature and relative humidity are observed at noon. One day is in June (DL_1), and the other in September (DL_2). Further assume that the only change which occurs is the normal diurnal cycle. The two curves in Fig. 2 represent a continuous trace of the effect of TP and RHD on the drying rate. The actual effect need not be defined, as the relationship will be evident with any set of curves. Each curve represents the relative effect of TP and RHD between sunrise and sunset which must occur, if identical noon conditions are to be attained on both days. The 12 hour average values of the cross product of TP and RHD are a function of the areas under the respective curves.

Since the final moisture content of fast responding fuels is governed more by the value being approached than the rate of change, the influence of day length is reduced considerably. It seems reasonable to hypothesize however that in the case of slower responding fuels, where the rate of change becomes the dominating influence that day length will be one of the more important factors governing the moisture content of slow responding fuels.

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BELOW THE FIBER SATURATION POINT

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NOTE

This paper is the third in a series dealing with the moisture content of forest fuels. Other papers in the series are:

I   A Review of the Basic Concepts

Department of Forestry and Rural Development

Information Report FF-X-14

II   A comparison of Moisture content Variations Above the Fibre Saturation Point Betweeen A Number of Fuel Types

Department of Forestry and Rural Development

Information Report FF-X-15

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temperature and surface relative humidity should be used. If it can be shown, however, that other more easily measured variables which influence the primary ones are also related to fuel moisture, a good working relationship will have been developed, such as the correlation between degree days and fuel oil consumption which is in common use today.

EXPERIMENTAL PROCEDURE

A. Data Collection

For this study fuel moisture data were made available for samples which had been exposed during the summer of 1967. The following discussion is a summary of the ordering, planning and supervision of the collection of the fuel moisture data, all of which were done by Mr. C.E. Van Wagner.[1] The actual data collection was done by Mr. Van Wagner, with the aid of a technician and forestry students.

The fuel samples had been protected from rain by covers which were placed about 24 inches above the ground to permit adequate circulation. The samples were placed in baskets, described by Wright (1932). They are made of wire, with a nylon mesh bottom which retains the sample intact. They were placed in the ground so that the top of the sample was level with the top of the litter layer. In this way it was hoped that the samples would behave in the same manner as the surrounding fuels and yet be easily removed for weighing. Three exposures were used:

1 - Wooden cover in the open (no sunlight enters) - Jack pine, match splints, Aspen leaves.

2 - Transparent polyethylene cover in the open - full sunlight, samples same as in 1.

3 - Transparent polyethylene cover in a mixed forest stand (about 70% crown closure) - samples same as in 1.

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[1] *Research Scientist, Petawawa Forest Experiment Station, Chalk River, Ontario.*

The range of weights of the various samples is given in Table 1.

Table 1   Oven-dry weights of samples in field tests.

Sample	Weight (lbs/ft of surface area) [1]
Jack pine (light)	.043 to .071
Jack pine (heavy)	.132 to .142
Match splints	.202 to .211
Quaking aspen	.050 to .057

All samples were weighed several times each day. All samples were exposed for about two months and brought into the laboratory and oven-dried. A new series of samples was then set out. In all, three series were used throughout the summer.

Meteorological observations were recorded by adjacent instruments described by Fraser and Farr (1965). Relative humidity and temperature were measured with a Fuess hygrothermograph exposed in a double louvred Stevenson screen. The accuracy of the instrument used is estimated at ±3% for relative humidity and ±2°F. for temperature. Wind speed was measured with an MSC type 45B contact-type combined anemometer and wind vane mounted 35 feet above the ground. Continuous records were obtained with an MSC[2] type B anemograph. A continuous record of the time, duration and intensity of rainfall was obtained with an MSC type B-1 10-inch tipping-bucket rain gauge receiver in combination with an MSC type B electric impulse rain gauge recorder. A Bellani pyranometer was used to measure total daily radiation on a spherical surface. All of the weather data used in the present study was also provided by Mr. C.E. Van Wagner.

1/ Computed by the author from total weights provided by Mr. C.E. Van Wagner.
2/ Meteorological Service of Canada.

The fuel samples in the open were located about 50 feet from the weather station where the above instruments were located. The samples in the mixed forest stand were about 250 feet away.

Fig. 1 is a photograph of the weather station and the stand in which one series of samples was exposed. The open plots can be seen directly behind the station enclosure. The forest plot was just to the left of the Red Pine stand.

B.   Data Analysis

The basic weather variables studied were: relative humidity (RH), temperature, wind, and day length. Relative humidity deficit (RHD = 100 - RH) was used during the day so that it could be combined with temperature. As one increases, so does the other, and their effect on fuel moisture is in the same direction rather than opposite.

Temperature and RHD were further stratified as follows: Instantaneous observation (single observation at the time of fuel moisture measurement), two, four and six hour averages just before the measurement, a twelve hour average (6 a.m. to 6 p.m. for day and 6 p.m. to 6 a.m. for night). Instantaneous and two hour average minimum and maximum values were also obtained. All temperature averages were obtained by measuring the area under the tracing on the hygrothermograph chart (above zero). RHD measurements were obtained from the area above the tracing (assuming a maximum value of 96%). The changes in all of the above combinations of temperature and RHD between the morning and afternoon measurements were determined, and were also used.

Figure 1   *The Standard Weather Station, and Fuel Moisture Exposure Sites at the Petawawa Forest Experiment Station, Chalk River, Ontario*
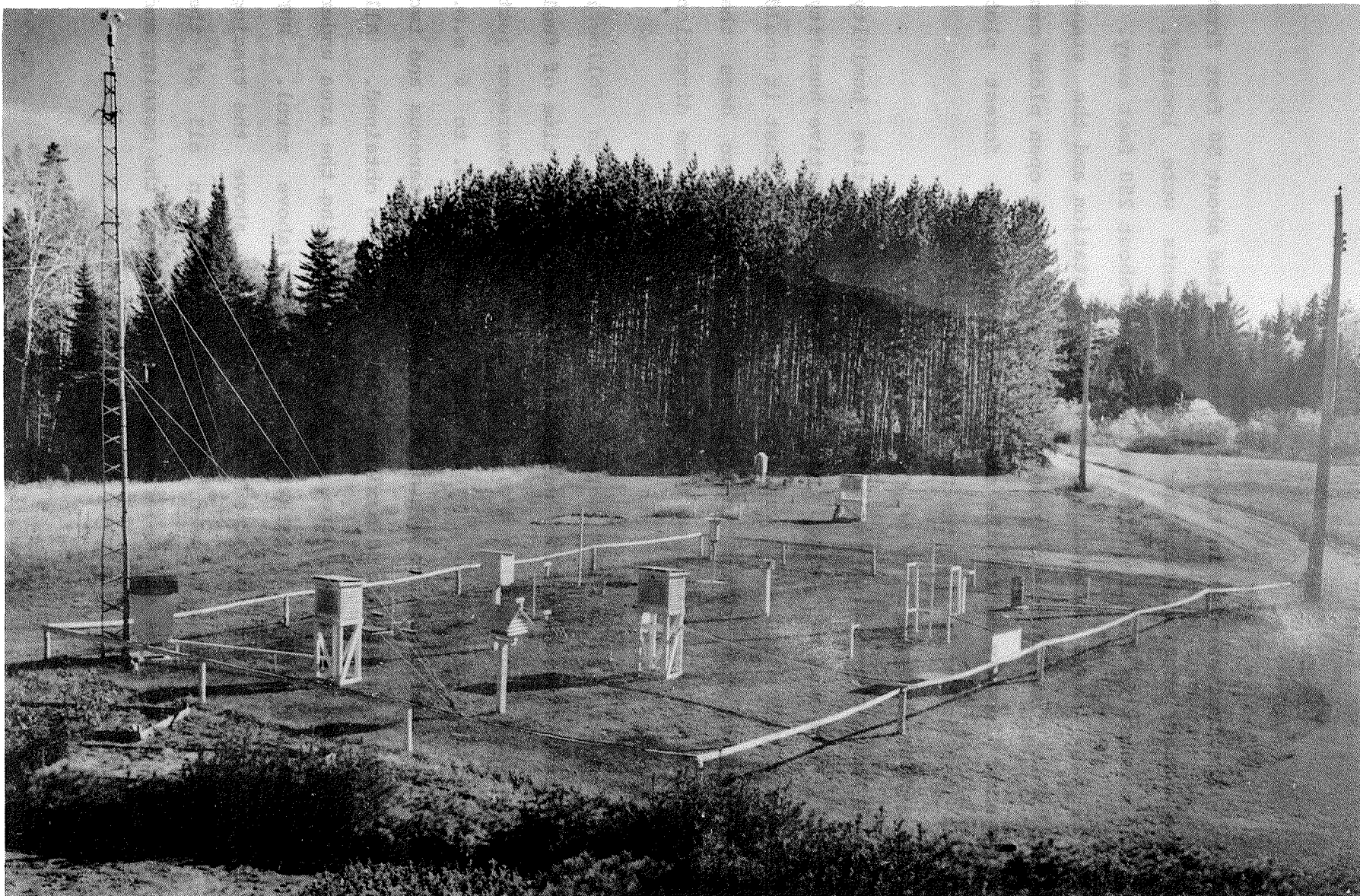
Photo courtesy of the Petawawa Forest Experiment Station

The basic values of temperature and RHD were used to determine values for equilibrium moisture content and vapor pressure deficit, which were also studied. Lastly, selected combinations of variables were also investigated.

All of the above variables were correlated with fuel moisture measured in the morning and afternoon. The fuel moisture was an average of the three fuel types exposed (match splints, aspen leaves and jack pine needles). Starting moisture content (12 to 24 hours previous) was also correlated with final fuel moisture. The change in moisture content was also correlated with selected weather variables.

Prior to analysis, some of the data were eliminated as follows:

1. Any moisture content measurements greater than 50% were assumed to have been influenced by liquid water and were eliminated.

2. All days during which the moisture content increased were discarded. Nights when the moisture content decreased were also eliminated. The purpose of this was to separate the gain and loss of water so that each could be studied separately.

3. All morning moisture content measurements made prior to 7:30 a.m. or after 9:30 were discarded. All afternoon measurements made prior to 3:00 p.m. or after 5:00 p.m. were also eliminated.

All of the data was then analyzed with the aid of a computer, using a multiple regression technique. The results are discussed in this paper.

RESULTS AND DISCUSSION

Although the main purpose of this paper is to determine the influence of meteorological factors on fast responding fuel moisture, the variety of fuel types and exposures which were used permits a number of empirical observations on the influence of factors other than weather. Therefore, prior to discussing the effect of weather on fuel moisture, some observations will be made on the differences: due to exposure, due to the season, and between species. Some observations on moisture content lag will also be presented.

A.   Effect of Exposure

The moisture content of a particular fuel is a complex function of the environmental conditions which surround it. Anything which alters the environment around the fuel may therefore indirectly affect its moisture content. In the present investigation three environmental conditions were considered. They were: in the open, under a transparent plastic cover, a wooden cover in the open, and a plastic cover in a stand of trees. The average moisture contents under each of these conditions are listed in Table 2.

Table   2   Seasonal Average Moisture Content by Site
(in Percent of Oven Dry eight)

	Forest-plastic	Open-wood	Open-plastic
Morning	24.4%	21.6%	16.4%
Afternoon	19.0%	15.4%	8.1%

It is readily apparent that both morning and afternoon average moisture contents are higher in the stand than in the open. Furthermore, it can be noted that the difference between the average morning and afternoon moisture contents (5.2%) is lowest in the stand. These results are quite reasonable, considering the manner in which a stand of trees modifies the local environment. Afternoon temperatures are lower in a stand than in the open, and relative humidities are higher. Therefore, afternoon moisture contents would be higher in a stand. In the morning, differences between the stand and open conditions would be much less than in the afternoon. Overnight relative humidities are normally high in the stand and in the open, and temperatures tend to be slightly higher in a stand.

As the diurnal cycle enters the night phase, fuel in the open will start to gain moisture first, and it will absorb it at a faster rate. It will start first, because the moisture content is lower in the open, and it will increase faster because it is farther from equilibrium conditions at high relative humidities. It should be remembered, however, that the initial moisture content in the stand is considerably higher than in the open. In fact, it is so much higher that even after exposure for an entire night, the moisture content of fuels in the open has not risen as high as the initial value in the stand. At the same time, fuels in the stand are also adsorbing water, although at at slower rate than those in the open. Therefore, fuel moisture in the stand would also be expected to be higher in the morning.

Average moisture contents under the wooden cover in the open are lower than under the stand, but higher than under the plastic cover. This is reasonable, since solar radiation cannot reach the ground and raise fuel surface temperatures. Relative humidities are correspondingly higher under the wooden cover. Keeping this in mind, the reasoning used when comparing open conditions with the stand can also be applied to the wooden shelter, with only minor modificiations.

B.   Seasonal Differences

If all fuel samples had been identical, their average moisture contents would be related to the average environmental conditions which prevailed during each series. Table 3 lists the average moisture contents and selected weather conditions by series.

Table 3   Average Moisture Contents and
               Weather Conditions by Series
               (in Percent of Oven Dry Weight)

Series	Morning			Afternoon			Weather(4pm)*		
	forest	wood	plastic	forest	wood	plastic	DL	TP	RH
1.	–	22.9	13.8	–	16.4	7.8	15.5	68	47
2.	27.8	22.9	16.7	22.8	16.9	9.9	14.8	72	51
3.	20.6	18.4	16.6	16.8	13.8	7.0	13.3	54	48

   * DL = day length in hours
     TP = temperature in °F.
     RH = relative humidity in percent.

It is apparent that the average moisture content of the third series is substantially lower than the other two. Moisture contents under the plastic shelter in the morning are an exception to this, and will be discussed subsequently. The average weather conditions indicate that the third series should

have the highest average moisture contents. Average day length and temperature are both lower during the latter part of the season. This implies that moisture contents should be higher. There is very little difference in the average relative humidity throughout the season. From these observations it is concluded that the third series of samples was different from the previous two. No information is available as to the reason for this difference.

The average moisture contents of the samples under the plastic shelter did not follow the same pattern as did the samples on the other two sites throughout the season. It is believed that the reason for this is related to the time of sunrise. At the site on a clear day, sunshine reaches the plot as early as 5:30 a.m. in June, and about 7:45 a.m. in October. Looking at the average moisture contents, it can be seen that the morning value of the first series is considerably lower than the other two. This is a good indication that in the present study, morning moisture contents of fuels exposed to sunlight do not reflect the culmination of overnight conditions only. Instead, they are a function of both overnight conditions, and a short exposure to a daytime environment.

The fact that there is no difference between the morning measurements of the second and third series under the plastic may be an indication that the changing time of sunrise is just offset by the difference of the samples used in the third series. This possibility is strengthened by the fact that the second and third series are different in the afternoon. Further, since afternoon moisture contents depend on the morning values, (as will be

discussed), the series 1 measurements in the afternoon under the plastic shelter in the open are reduced in proportion to the reduction in morning values. From this data, it is concluded that morning moisture contents in the open have to be measured prior to sunrise to be considered representative of night conditions only.

C.   Differences between Fuel Types

The average moisture contents of the three types of fuel tested were not equal. They are listed in Table 4.

Table 4   Average Moisture Content by Fuel Type
                       (in Percent of Oven Dry Weight)

	Match Splints	Jack Pine needles	Aspen leaves	Average
Morning				
Plastic	14.4	15.0	19.9	16.4
Wood	17.6	19.2	28.1	21.6
Forest	19.0	22.5	31.2	24.2
Afternoon				
Plastic	7.8	8.9	10.8	9.2
Wood	13.1	15.4	17.7	15.4
Forest	15.7	19.1	22.4	19.1
Average	14.6	16.1	21.6	

As can be seen from the table, the match splints had the lowest moisture content in every case. The average was two percent less than the Jack pine needles, and seven percent less than the Aspen leaves. Further, the Aspen leaves had the highest moisture content in every case. Based on the work of Dunlap (1929), it was concluded by the U.S. Forest Service (1966) that hardwood leaves have an equilibrium moisture content which is a constant six percent higher than wood in the 20 to 70 percent relative humidity range. This is in very close agreement with

the findings of the present study, except that the difference may not be constant, as will be discussed.

The differences were highly significant in almost every case. The significance of the differences can be summarized as follows:

1. Aspen leaves and match splints - .01 - all observations.
2. Aspen leaves and Jack pine needles - .01 - five observations; .02 - wood, afternoon.
3. Jack pine needles and match splints - .01 - forest, morning and afternoon, wood, afternoon; .05 - wood, morning and plastic, afternoon; .25 (approx.) - plastic, morning.

Therefore, it is with a high degree of confidence that it is concluded that the average moisture contents of the three fuel types are significantly different in the absence of rain.

It can also be noted that the differences are greater in the morning than in the afternoon. Also the differences increase as the amount of shading increases. This implies that the EMC curves of the three fuel types are not parallel, but rather that the differences increase as the moisture content increases.

These differences are of fundamental importance. They imply that, on the average, an indicator stick will give lower moisture content readings than the actual fast responding fuel moisture in the same environment. This assumes, of course, that the time lag of the fuels and the stick are identical. A further implication is that while an average moisture content for a large region may be sufficient for administrative purposes, any specific application of fuel moisture to burning intensity will require

that the moisture content be directly representative of the fuels in the specific area.

D.   Moisture Content Lag

It has often been assumed that actual fine fuel moisture is never very far from equilibrium with the environment at any given instant, (in the absence of rain). Use of the term equilibrium is actually a misnomer as it implies steady state conditions, which are not normally attained in nature. Regardless of the term used, the implication is that the moisture content of fine fuels changes very rapidly in response to environmental changes.

To test this theory, both morning and afternoon moisture contents were correlated with the previous afternoon and morning measurements respectively. The results are presented in Table 5. The morning measurements are 16 hours after the previous afternoon, and the afternoon readings are 8 hours after the morning observations.

Table   5   Correlations between Initial
                     and Final Moisture Contents
                          (one-half day apart)

	Morning	Afternoon
Plastic	.688	.556
Wood	.698	.716
Forest	.899	.880

The high correlations between measurements which are several hours apart are a strong indication that fine fuel moisture does not change rapidly. In fact, afternoon moisture content is highly dependent on the previous morning value. Similarly, morning moisture contents are highly dependent on the value attained the previous afternoon.

It is interesting to note that fuels under the stand of trees show the highest correlation between subsequent measurements. As mentioned, these fuels also showed the smallest daily change. On the other hand, the samples in the open, under full sunlight show both the highest daily change and lowest correlation between subsequent measurements. The wooden shelter lies between the extremes in both cases. The fact that these two observations support each other lends additional weight to their validity.

Table 6 lists the correlation between afternoon moisture contents and previous afternoon values (24 hours apart).

Table 6   Correlation between Afternoon Moisture Contents
(24 hours apart)

Plastic - .484   Wood - .335   Forest - .810

The correlations in the open are much lower than values which are only half a day apart, but they are still significant. In the stand, the correlation is still quite high. These correlations indicate that fine fuel moisture at any instant is dependent on the moisture content which had been reached at least 8, and in some cases as much as 24, hours earlier.

Before leaving this subject, it should also be mentioned that initial moisture content greatly influences the amount of change which occurs on a given day. If fuel moisture is close to the final value which is being approached, there can be little change, regardless of the environmental conditions. The correlations between initial moisture content and amount of change presented in Table 7 indicate this relationship, especially during daytime conditions.

Table 7   Correlation between Initial Fuel Moisture
and Change in Moisture Content

	Day	Overnight
Plastic	.583	.312
Wood	.662	.226
Forest	.738	.344

E.   Influence of Weather

When considering the influence of weather on the moisture content of fast responding fuels, both actual moisture content and rate of change must be considered. Table 8 lists the correlations between a number of basic weather variables and final moisture content. Table 9 gives corresponding values for moisture content change. A complete list of correlations can be found in the appendix. Only the magnitude of the correlation is considered here. The direction (+ or -) will be discussed subsequently.

Table 8   Correlation between Weather Variables and Fuel Moisture

Variable(1)	Morning			Afternoon		
	Plastic	Wood	Forest	Plastic	Wood	Forest
RHD(2)	.519(3)	.215	.059	.636	.626	.634
TP	.030	.419	.740	.239	.086	.276
W	.014	.017	.213	.246	.094	.108
EMC	.465	.109	.175	.604	.526	.557
VPD	.003	.423	.762	.174	.113	.292
DL	.276	.350	.709	.179	.240	.526

(1) Instantaneous observations taken at 8 a.m. and 4 p.m. for morning and afternoon respectively.

(2) For a complete list of variable names and descriptions, see the appendix.

(3) For the significance of the correlations, see the appendix. As a general rule of thumb, .250 may be considered significant at the 95% level of confidence.

Table 9   Correlation between Weather Variables
           and Fuel Moisture Changes

Variable	Daytime Change			Overnight Change		
	Plastic	Wood	Forest	Plastic	Wood	Forest
RHD	.162	.246	.174	.451	.279	.135
TP	.212	.377	.480	.044	.153	.351
W	.247	.007	.023	.021	.101	.030
EMC	.215	.276	.235	.416	.251	.069
VPD	.275	.359	.435	.034	.155	.317
DL	.018	.380	.524	.147	.065	.305

It is immediately apparent that the correlation between moisture content (MC), or change in moisture content (Δ MC), and any variable is quite different, depending on whether the observation is in the morning or afternoon. This difference suggests that the amount of influence exerted by any given factor may vary, depending on environmental conditions. It also suggests that the daytime variable which exerts the greatest influence is not the same variable which limits overnight changes.

A distinction must be made between limiting and controlling. The moisture content of a particular fuel is controlled by the environment which surrounds it. If left for an infinite time at constant conditions, fuel moisture will eventually reach an equilibrium value. In this case, equilibrium moisture content may be considered the ultimate limiting factor. On the other hand, if the fuel is exposed for a short period of time, it is still controlled by the same environmental factors, but the final value is limited by the sorption rate, and length of exposure.

In a natural environment, however, there is no such thing as equilibrium, (assuming a response time lag greater than zero), because the environment is constantly changing. As the

environmental factors proceed through the diurnal cycle, moisture enters or leaves the fuel depending on whether the fuel vapor pressure is greater or less than atmospheric vapor pressure. This vapor pressure difference (or potential) influences the rate of the gain and loss of water vapor.

Before proceeding any further, it should be emphasized that relative humidity and atmospheric vapor pressure are not the same variable. They do not have the same effect on fuel moisture, and are not interchangeable. Atmospheric vapor pressure is related to the rate at which the moisture content changes. Relative humidity is related to the ultimate moisture content which will be reached. This important, but often overlooked, difference was noted as early as 1935 by Wright (Wright, 1935). This distinction must be borne in mind whenever the relationship between fuel moisture and atmospheric vapor pressure is being considered.

A number of factors may limit the moisture content which is reached after a limited exposure (half day or less) to a given environment. During a normal day (high temperatures, and low relative humidities), atmospheric vapor pressure deficit is high and fuel moisture could change rapidly. The most important limiting factor would therefore be the value which the fuel moisture would reach if left at the minimum afternoon relative humidity for an extended period. This assumes that environmental conditions change more rapidly than fuel moisture.

During a normal night (low temperatures, high relative humidities), atmospheric vapor pressure deficit is low, and the sorption rate is also low. In this case, sorption rate and

length of exposure become limiting rather than the value which is being approached. As a further refinement, when the atmospheric vapor pressure deficit approaches zero, as commonly occurs overnight, temperature becomes more limiting than vapor pressure deficit. This is because in a saturated atmosphere a plentiful supply of water vapor is present, (assuming adequate circulation), and the most important limiting factor then becomes the rate at which moisture will diffuse into the fuel. Temperature is one of the factors which controls the rate of diffusion.

The data presented in Table 8 supports the theory of limiting factors. Afternoon relative humidity deficit (RHD) and equilibrium moisture content (EMC) show high correlation with afternoon moisture content. EMC under full exposure was slightly better than under shaded conditions. This is to be expected, since vapor pressure deficit would be highest under full sunlight.

In contrast, morning values of RHD and EMC show poor correlation with morning moisture content under the wooden shelter and in the stand. As previously discussed, time of sunrise greatly affects morning moisture content under the pastic shelter, so that it is beginning to be affected by daytime conditions.

Looking at temperature (TP) and vapor pressure deficit (VPD), it can be seen that they are in direct contrast to RHD and EMC. TP and VPD show relatively high correlations with fuel moisture in the morning, except for the open plastic shelter. They show no significant correlation with afternoon moisture content, except in the stand.

The data in Table 9 indicates that changes in moisture content are more difficult to predict than final values. None of the correlations between the various factors and moisture content change are very high. It is apparent that there are other factors which complicate the simple relationships which are under consideration here. This problem may be the cause of the lower overnight correlations between initial moisture content and moisture content change presented in Table 7.

From Table 9, it can be seen that VPD has a higher average correlation with moisture content change than the final value. VPD and TP also show higher correlations with daytime changes on all sites, and overnight changes in the stand than any other variables. As mentioned, measurements under the open plastic shelter in the morning have been affected by a short exposure to solar radiation. It is possible that the wooden shelter was also affected, although to a lesser degree. Although the correlations are not high, they tend to confirm the relationship between VPD, TP, and sorption rate. On the other hand, RHD and EMC show lower correlations with daily moisture content change, and overnight change in the stand.

The effect of wind is not readily apparent from the data. In most cases, the correlations between wind speed and moisture content were not significant. It is possible that only a simple measurement of wind would be more appropriate. The difference may simply be a matter of whether there is no wind, or a little wind. The significance of these distinctions is whether or not there is enough atmospheric circulation to maintain a fresh supply of air at the surface of the fuel. This may require only

a very light wind. So long as atmospheric mixing is sufficient,
it may not matter how much there is, as another factor becomes
limiting. Another difficulty of assessing the effect of wind is
the fact that it is a relatively minor factor, and the more
important variables overshadow any effect that it might have.

It is interesting to note the correlation between day length
(DL) and fuel moisture. It is somewhat similar to temperature,
in that the correlation is lower during the day than at night.
The correlation also increases as the amount of shading
increases. Since the length of exposure for either morning or
afternoon measurements is constant (16 and 8 hours respectively),
day length influences total daily change through its effect on
the average vapor pressure deficit, and temperature. This is
discussed in some detail in the section on slow responding fuels.
The relationship between DL and MC, or Δ MC lends further support
to the theory of limiting factors.

With respect to the direction of correlation (positive or
negative), RHD and EMC behaved as expected in all cases. The
correlation with RHD was negative, and with EMC it was positive,
with respect to final moisture content. This simply indicates
that as EMC (which is a function of relative humidity) increased,
fuel moisture also increased.

TP, VPD, and DL were positively correlated with fuel
moisture in the morning. They were also positively correlated
with overnight moisture content change. From the previous
discussion, this is exactly as it should be.

Daily moisture content changes were negatively correlated with the above three factors. It should be remembered that moisture content decreases during the day, and a negative correlation simply indicates that as any of the above three factors increases the amount of drying increases also. The correlation with afternoon moisture content was much less in agreement with theoretical considerations. Increasing TP, VPD, or DL should decrease the final afternoon moisture content, especially since it was just shown that a faster drying rate accompanies an increase in any of the above factors.

In many cases, the correlations between the above variables and final afternoon moisture content were positive. This would seem to indicate that increasing TP, VPD, or DL increases the final moisture content, which is exactly opposite to what should happen. Looking back to Table 3 however, it can be seen that the third series has a substantially lower average moisture content than the other two. Average day length and temperature are also lower during the latter part of the season. The positive correlations are therefore meaningless. They are simply the result of independent events occurring simultaneously. The term independent is used because it is not felt that the lower average moisture contents in the third series are in any way related to the lower average temperatures or day lengths. This portion of the data is therefore considered inconclusive.

It is likely that the lower average moisture content in the third series is partially responsible for the positive overnight correlation between the above mentioned variables and morning fuel moisture. There is no way to determine how much of the

correlation is due to the differences in the third series. It is felt, however, that much of the correlation is due to the previously discussed relationship between overnight conditions and morning moisture content. There are three reasons for this:

1. The positive correlation is theoretically correct.
2. The correlations are considerably higher at night than during the day.
3. Both day and night correlations between TP, VPD, DL, and moisture content change behaved as expected with respect to the direction of correlation.

The last point to be considered is the fact that the correlations decrease as the amount of shading decreases. Much of the error is believed to be caused by the effect of sunshine on fuel surface temperature. While standard ambient temperature measurements show the effect of the presence or absence of clouds, the difference is not nearly as great as when temperatures are measured at the earth's surface. For this reason, it is believed that fuel surface temperature or a function of ambient temperature and hours of sunshine would give better correlations with unsheltered fuel moisture. Naturally, ambient relative humidity would have to be adjusted for the fuel surface temperature.

F.   Regression Equations

Several functions of each of the basic variables were correlated with fuel moisture to determine the most appropriate form to use in a regression equation. A complete list of all correlations can be found in the appendix. Only the general results will be discussed here.

No consistent improvement in correlation was obtained by squaring any of the variables. Furthermore, the small improvements which were made in some cases were not sufficient to warrant the additional complication.

It was not possible to obtain a consistent improvement in the average correlation of all the basic weather variables by using average conditions for extended periods of time. In some cases, the two or four hour averages were better than the instantaneous observations. The comparison is complicated by the fact that as the correlation between moisture content and one variable increased, with an increasing time period, another variable decreased. There is a strong indication, however, that the correlation with any individual variable is dependent on the length of time over which that variable is averaged. The differences between variables is most likely due to the different mechanism through which each influences fuel moisture. The relationship between correlation and time period was more evident in the morning than in the afternoon. In general, the instantaneous or two hour averages had the highest correlations in the afternoon.

Maximum and minimum daily measurements of the basic variables had higher average correlations with fuel moisture measurements than the instantaneous values in most cases. Other than the open plastic shelter in the morning, the only case where minimum values showed a significantly lower average correlation was the stand in the morning.

Both morning and afternoon moisture content measurements are taken shortly (2 to 4 hours) after the maximum and minimum weather values have been reached. Because of the time lag of the fuels, it is quite reasonable that the moisture contents are most closely related to the conditions of a few hours previous. The maximum and minimum weather measurements are also more closely related to the value which fuel moisture is approaching, than the two or four hour averages.

There was little or no improvement obtained by comparing two hour average maximum and minimum values with instantaneous observations. It should be mentioned, however, that both were taken from a hygrothermograph chart and that comparison of instantaneous values obtained with maximum and minimum thermometers might have shown a greater difference.

Instantaneous observations at noon had slightly higher average correlations with afternoon moisture content than 4 p.m. readings, except under the plastic shelter in the open. The correlations were lower than for maximum observations. Since noon values are a function of average conditions preceding the afternoon moisture content measurement, this is not surprising. The differences are not great enough, however, to conclude that there will be any improvement in the accuracy of estimating afternoon fuel moisture by substituting noon observations for 4 p.m. values. It would be more appropriate to conclude that either one could be used with about the same accuracy. Of course, the constants would be different.

There has already been some discussion on moisture content change. Actual weather variables and the daily change in the weather variables were correlated with daily change in moisture content (Δ MC), and daily change in the logarithm of the moisture content, (ΔLMC). The only variable which had a high correlation with Δ MC was initial moisture content. The correlation with all other variables was lower than when actual moisture content was used. It was expected that the use of Δ LMC would eliminate the need to use the initial moisture content. Unfortunately, this function does not appear to have any relationship to daily moisture content changes. All correlations were very low, or not significant. From this, it is concluded that change in moisture content is a more difficult function to predict, than actual moisture content. For this reason, all equations which were derived attempt to estimate final moisture content only.

When deriving equations to estimate fast responding fuel moisture, the average moisture content of the three fuel types was used. There are three reasons why this was preferred to deriving individual equations for each fuel type. They are:

1. The moisture content of the individual fuels had greater variation than the average of the three types.

2. There is little information available as to what effect the differences between the fuel types have on their moisture content.

3. There is almost no information on how these differences alter the effect of the various weather parameters.

If it is desired to calculate the moisture content of a particular fuel type, one can adjust the value obtained from the equation according to the ratio of the particular type to the average, as given in Table 4.

It has been pointed out that the third series of samples had a lower average moisture content than the other two. Since it has also been shown that final moisture content is dependent on the initial value, all equations include initial moisture content. With this factor included, it is assumed that the effect of the difference in the third series has been eliminated. Therefore, all data has been lumped together to derive the equations.

Altogether, 12 equations have been derived. One group predicts afternoon moisture content on the basis of observations which are 24 hours apart. There is one equation for each site. One set of equations uses instantaneous and maximum values only. The other set uses the best possible variables available.

The second group estimates both morning and afternoon moisture content on the basis of observations one half day apart. Because there was only very slight improvement when the best possible variables were used for the 24 hour prediction, only instantaneous and maximum (or minimum where appropriate) values are used. The variables listed were selected by a computer, using a stepwise multiple regression program. A complete list of variables from which the three were selected as well as additional information on the equations can be found in the appendix.

TABLE 10

BEST THREE VARIABLE COMBINATIONS FOR PREDICTING FAST RESPONDING FUEL MOISTURE

Site	Variables	Constant	Coefficients			R^2	Confidence[1] Limits	Error[2]
24 Hour Afternoon - Best								
Forest	SMC, RHD4, DL	11.6716	.389360	-.176129	.630856	.890	13.8	2.6
Wood	EMCM, DL, TP4 x RHD4	-12.7447	.684850	2.16564	-.002807	.776	31.7	5.2
Plastic	EMCM, SMC, RHD4	8.41175	.252923	.364254	-.097767	.665	43.6	3.9
24 Hour Afternoon - Instantaneous								
Forest	SMC, RHM, DL	- 6.41757	.384787	.199972	.663083	.864	15.4	2.9
Wood	EMCM, DL, VPDI	-17.9225	1.41402	1.72795	-.097760	.718	35.6	5.8
Plastic	EMCM, SMC, EMCI	.041279	.387002	.339891	.243607	.639	45.2	4.1
8 Hour Afternoon - Instantaneous								
Forest	SMC, RHM, EMCI	- .189210	.542712	.096984	.184766	.904	13.1	2.5
Wood	SMC, RHM, DL	- 6.60311	.333375	.194593	.475962	.779	24.0	3.7
Plastic	EMCM, SMC, TPI x RHDI	1.38412	.522908	.270202	-.000360	.615	44.6	4.1
16 Hour Morning - Instantaneous								
Forest	SMC, RHM x TPM, EMCM	- 2.39682	.634613	.002122	.188570	.924	12.3	3.0
Wood	SMC, RHM x TPM, TPM	4.59912	.590959	.005612	-.354834	.648	28.6	6.2
Plastic	SMC, RHDI, TPM	9.87059	.622568	-.083842	.065781	.651	25.6	4.2

[1] For an individual estimate at the mean value of the independent variable at the 95% level of confidence. Values are in per cent of the predicted moisture content.

[2] Actual moisture content (% oven dry weight)

The best three variable combinations are listed in Table 10. The variables are listed in the order of selection. It can be seen that no two equations use the same three variables to estimate fuel moisture. Since each of the three sites are under the influence of different environmental conditions, it is not surprising that this should be the case. On the other hand, certain variables are used in a number of equations. For example, the only difference between the best possible 24 hour combinations and the instantaneous values is the substitution of a four hour RH function for a similar instantaneous function.

In comparing the instantaneous equations, it can be seen that a number of functions are repeated several times. SMC is found in eight equations, and EMCM in four. RHM is found in three of the six afternoon equations, and RHM x TPM is found in two of the three morning ones. TPM alone is also found in two of the three morning equations, although as the third variable in both cases. It can be said, therefore, that the choice of predictor variables is in agreement with the correlations previously discussed.

The possibility of deriving a general equation, using the most commonly found variables, was considered. The usefulness of such an equation is debatable, however. It was felt that if a separate equation for each site was too complex, one of the three could be used as a base, and the value obtained could be adjusted according to the relationships between the sites which are presented in Table 2.

Looking at the value of R^2 and the confidence limits, it is apparent that little is gained by using the more complex variables for the 24 hour equations. Making the calculations in two steps also shows little improvement over the 24 hour equation. Further, the daytime equations are based on measured starting moisture contents. If values of SMC were calculated using the morning equation, the errors would no doubt eliminate any possible gain made by using the two step procedure.

The most accurate equations are those for the stand. At the 95 percent level of confidence an individual prediction will be within $\pm$ 12% to 15% of the actual value[1] depending on the equation used. This error is less than three percent, in terms of actual moisture content. The equations for the wooden shelter have an error in the range of 25% to 35%, and the open equations have a 25% to 45% error. These errors are equivalent to about five percent and four percent respectively, in terms of actual moisture content. It should be remembered, however, that these errors are for an individual prediction. The average of a series of predictions will be much closer to the actual average moisture content.

The equations in this paper were compared with those developed by Storey (1965), for predicting slat and dowel moisture. The results show that the stand equations are slightly more accurate in terms of percentage error. Those for the wooden shelter have about the same error, and those in the open have a slightly greater error. It is believed, however, that if fuel surface temperature and relative humidity were used, the accuracy of the two equations in the open would be improved considerably.

[1] *At the mean values of the independent variables.*

It should be mentioned that Storey also considered rainfall, which was not the case in the present paper.

In conclusion, if only afternoon moisture content is of interest, the 24 hour equations, using instantaneous values appears to be the best choice. There are, of course, numerous instances where morning moisture content is of importance, such as estimating the intensity of a prescribed or wild fire early in the morning. In these cases, the two step method may be used to advantage.

G. Conclusions

1. There is a significant difference in the average moisture content on different sites. The stand averaged three percent higher than the wooden shelter, and ten percent higher than open conditions under full sunlight. The differences are greater in the morning than in the afternoon.

2. Average daily change in moisture content is greatest in the open, where it averaged about eight percent. It was less under the wooden shelter, (six percent), and in the stand, (five percent).

3. The three types of fuel tested have significantly different average moisture contents. Match splints are the lowest, followed by Jack pine needles, which were two percent higher, and Aspen leaves, which averaged seven percent higher. These differences increased as the moisture content increased.

4. Afternoon and morning moisture contents are highly correlated with values measured the previous morning and afternoon respectively. Afternoon moisture contents in the stand (24 hours apart) are also highly correlated.

5. Daily moisture content change is highly correlated with initial moisture content. The correlation is much poorer for overnight change.

6. Afternoon moisture content is most limited by the value which is being approached. Morning moisture content is limited by the average sorption rate.

7. Vapor pressure deficit and temperature are the weather variables which are most closely related to sorption rate. Relative humidity is most closely related to the moisture content which is being approached.

8. It is easier to predict final moisture content than daily moisture content change.

9. Extending the time period over which a variable is averaged did not improve the average correlation in all cases. It did tend to improve correlation with individual variables.

10. Squaring the variables did not improve the correlation with moisture content.

11. Maximum afternoon and minimum morning conditions had higher correlations with fuel moisture than instantaneous values.

12. Either noon or 4 p.m. observations may be used to predict afternoon moisture content with about the same accuracy.

13. Fuel moisture can be predicted with greater accuracy in the stand with the equations which have been developed. The increased error in the open is believed to be due to the effect of sunshine on fuel surface temperature.

14. There is little or no accuracy gained by calculating moisture content twice a day rather than on a 24-hour basis. This assumes that morning moisture content is not required for other purposes.

SUMMARY

To study the effect of weather on fuel moisture below the fiber saturation point, fuel moisture data for several samples of match splints, Jack pine needles, and Aspen leaves which had been exposed in the field were analyzed. They had been placed under covers as protection from rain and dew. They had been exposed through an entire summer in a forest stand, and in the open.

The effect of site on fuel moisture was readily apparent. The average moisture content was highest in the stand. Fuels under the wooden shelter in the open averaged about three percent less, and under the plastic shelter about ten percent less than the stand. The amount of daily change was in direct contrast, with the samples in the stand showing the smallest diurnal variation of about five percent. The wooden and plastic shelters changed about six and eight percent respectively between morning and afternoon conditions.

There were significant differences in the three species of fuels tested. The match splints had the lowest average moisture content, both in the morning and afternoon. The Jack pine needles averaged two percent higher, and the Aspen leaves averaged seven percent higher than the match splints.

It was found that the moisture content of fast responding fuels does not change as rapidly as commonly assumed. Fuel moisture was found to be highly correlated with values which had been measured as much as 24 hours previously.

Based on correlations between a number of weather variables and fuel moisture, a theory of limiting factors is proposed: During the day, when sorption rates are high, the factor which exerts the greatest influence on afternoon moisture content is the equilibrium value which would be reached if the fuel were exposed at constant afternoon conditions for an infinite time period. Overnight, when sorption rates are low, the factor which exerts the greatest influence on morning moisture content is the sorption rate, and the length of exposure.

Relative humidity and equilibrium moisture content were found to be good predictors of afternoon moisture content. Temperature, vapor pressure deficit, and hours of darkness were found to be related to sorption rate. They are also good predictors of morning moisture content. The data were inconclusive with respect to wind.

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APPENDIX

This appendix contains the additional information referred to in the discussion.

List of Tables

In addition, this appendix contains a discussion of the vapor pressure deficit function used in the present study.

TABLE   1

LIST OF VARIABLE NAMES AND DESCRIPTIONS

1. Basic Variables

RH   -   Relative humidity in percent
RHD -   Relative humidity deficit (100 - RH)
TP   -   Temperature $^\circ$F
W   -   Wind speed - m.p.h.
DL   -   Day length - hours between sunrise and sunset
          For overnight measurements, 24.0-DL is used
SR   -   Solar radiation - cal/cm^2
EMC -   Equilibrium moisture content - % oven dry weight[1]
VPD -   Vapor pressure deficit - millibars see separate
          section on VPD in this appendix.

2. List of Suffices

--N   -   Noon observation
--I   -   Instantaneous observation (8 am, or 4 pm)
--2   -   2 hour average
--4   -   4 hour average
--6   -   6 hour average
--12 -   12 hour average
--M   -   Maximum or minimum observation, depending on the
           variable to which it is attached, and time of day
--C   -   Daily change in the variable named
--A   -   Afternoon
--O   -   Overnight

All of the above may be used singly, or in various
combinations.

3. Fuel Moisture

MC   -   Moisture content - % oven dry weight
ΔMC   -   Daily change in moisture content - % oven dry weight
ΔLMC -   Change in the logrithm of MC
SMC   -   Starting moisture content - % oven dry weight

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[1] *The equation used to estimate E.M.C. was derived by Simard (1968).*

TABLE   2a

CORRELATIONS BETWEEN WEATHER VARIABLES AND FAST RESPONDING FUEL MOISTURE IN THE STAND

Variable	Morning I	2	4	6	12	Afternoon I	2	4	6	12	Noon
RHD	.059	.059	.119	.150	.309	.634	.625	.618	.619	.525	.538
RHD^2	.032	.131	.158	.189	.249	.656	.638	.640	.643	.544	
RHDC	.035	.102	.095	.091	.321	.273	.350	.352	.358	.142	
RHDM	.094	.096				.605	.614				
TP	.740	.749	.741	.732	.645	.276	.285	.298	.312	.392	.316
TP^2	.754	.757	.743	.732	.622	.285	.302	.317	.332	.407	
TPC	.258	.289	.291	.319	.447	.445	.443	.354	.299	.471	
TPM	.728	.728				.297	.313				
W	.213	.042	.012	.009	.132	.108	.188	.183	.156	.081	.137
EMC	.175	.064	.076	.134	.248	.557	.535	.425	.348	.405	.370
EMC^2	.209	.105	.055	.104	.250	.509	.504	.348	.274	.371	
EMCC	.025				.024	.266				.206	
EMCM	.061	.051				.477	.513				
VPD	.762	.760	.710	.665	.599	.292	.315	.347	.391	.416	.358
VPD^2	.765	.750	.669	.607	.509	.267	.307	.353	.408	.412	
VPDC	.137				.047	.022				.003	
VPDM	.726	.725				.338	.352				
TP x RHD	.240	.095	.041	.018	.144	.334	.260	.258	.273	.218	.686
TPC x RHDC	.048	.049	.042	.068	.225	.395	.326	.343	.347	.044	
TPM x RHDM	.069	.058				.194	.208				
DL x RHD	.060	.025	.034	.060	.039	.404	.317	.319	.340	.309	
DL x TP	.538				.442	.388				.462	
DL x TP x RHD	.133				.231	.145				.046	
DL					.709					.526	
SMC	.899					.880					

TABLE 2b

CORRELATIONS BETWEEN WEATHER VARIABLES AND FAST RESPONDING FUEL MOISTURE UNDER THE WOODEN SHELTER IN THE OPEN

Variable	Morning					Afternoon					Noon
	I	2	4	6	12	I	2	4	6	12	
RHD	.215	.250	.300	.317	.410	.626	.677	.675	.670	.566	.610
RHD^2	.269	.300	.330	.360	.391	.632	.656	.657	.652	.542	
RHDC	.136	.218	.232	.256	.350	.344	.474	.489	.503	.288	
RHDM	.314	.335				.673	.681				
TP	.419	.471	.518	.516	.452	.086	.082	.086	.087	.142	.081
TP^2	.421	.472	.519	.517	.435	.096	.094	.098	.097	.151	
TPC	.159	.241	.282	.332	.252	.321	.418	.438	.370	.356	
TPM	.543	.542				.104	.090				
W	.017	.049	.073	.042	.057	.094	.121	.121	.125	.043	.067
EMC	.109	.138	.270	.306	.360	.526	.631	.576	.458	.511	.515
EMC^2	.060	.085	.249	.299	.346	.442	.609	.522	.366	.478	
EMCC	.060				.172	.258				.423	
EMCM	.231	.256				.621	.643				
VPD	.423	.472	.540	.518	.420	.113	.113	.122	.109	.160	.109
VPD^2	.405	.450	.511	.485	.360	.111	.117	.125	.101	.154	
VPDC	.048				.079	.178				.201	
VPDM	.530	.526				.144	.128				
TP x RHD	.111	.157	.190	.202	.306	.426	.464	.470	.481	.410	.629
TPC x RHD	.096	.132	.170	.200	.038	.464	.410	.426	.444	.128	
TPM x RHDM	.633	.648				.651	.659				
DL x RHD	.165	.211	.258	.272	.372	.427	.460	.461	.469	.416	
DL x TP	.417				.456	.163				.195	
DL x TP x RHD	.076				.277	.286				.302	
DL					.350					.240	
SMC	.698					.716					

TABLE 2c

CORRELATIONS BETWEEN WEATHER VARIABLES AND FAST RESPONDING FUEL MOISTURE IN FULL SUNLIGHT

Variable	Morning					Afternoon					Noon
	I	2	4	6	12	I	2	4	6	12	
RHD	.519	.436	.356	.370	.319	.636	.649	.668	.676	.643	.612
RHD^2	.521	.404	.316	.343	.326	.623	.633	.636	.635	.584	
RHDC	.117	.107	.077	.082	.061	.295	.358	.379	.397	.214	
RHDM	.178	.191				.703	.702				
TP	.030	.065	.168	.174	.173	.239	.228	.224	.217	.194	.220
TP^2	.017	.085	.196	.201	.188	.211	.201	.197	.190	.172	
TPC	.108	.240	.403	.436	.176	.375	.492	.489	.439	.169	
TPM	.285	.285				.218	.218				
W	.014	.100	.252	.220	.166	.246	.215	.186	.209	.185	.103
EMC	.465	.404	.173	.136	.282	.604	.623	.638	.774	.680	.618
EMC^2	.424	.379	.167	.143	.268	.550	.564	.608	.547	.671	
EMCC	.053				.010	.299				.382	
EMCM	.144	.157				.723	.716				
VPD	.003	.098	.299	.300	.193	.174	.164	.158	.140	.148	.160
VPD^2	.135	.116	.302	.298	.191	.120	.112	.113	.099	.111	
VPDC	.034				.090	.140				.171	
VPDM	.322	.318				.150	.157				
TP x RHD	.475	.411	.302	.306	.258	.607	.618	.630	.639	.606	.457
TPC x RHDC	.037	.099	.089	.103	.447	.411	.267	.284	.293	.210	
TPM x RHDM	.058	.072				.496	.418				
DL x RHD	.466	.467	.396	.412	.237		.644	.655	.660		
DL x TP	.264				.438						
DL x TP x RHD	.448				.202						
DL					.276					.179	
SMC	.668					.566					

TABLE   3

CORRELATIONS BETWEEN WEATHER VARIABLES AND ΔMC AND ΔLMC

Variable	Forest		Wood		Plastic	
	ΔMC	ΔLMC	ΔMC	ΔLMC	ΔMC	ΔLMC
Afternoon						
RHDI	.174	.126	.246	.095	.162	.094
RHDI^2	.320	.151	.253	.102	.004	.059
TPI	.480	.162	.367	.192	.212	.090
TPI^2	.552	.161	.377	.209	.211	.121
EMCI	.235	.118	.276	.111	.215	.107
VPDI	.435	.109	.359	.172	.275	.043
VPDN	.580	.187	.424	.257	.230	.107
VPDM	.487	.121	.376	.191	.246	.070
DL	.524	.115	.380	.002	.018	.008
W2	.023	.187	.007	.074	.247	.093
Morning						
RHDI	.135	.180	.279	.030	.451	.065
TPI	.351	.190	.153	.194	.044	.069
WI	.030	.038	.101	.151	.021	.045
EMCI	.069	.140	.251	.027	.416	.055
VPDI	.317	.186	.155	.174	.034	.032
VPDI2	.337	.124	.147	.158	.177	.064
VPDM	.298	.145	.168	.160	.218	.054
DL	.305	.116	.065	.178	.147	.009

TABLE   4

CORRELATIONS BETWEEN WEATHER CHANGES AND AFTERNOON
MOISTURE CONTENT CHANGES

Variable	Forest		Wood		Plastic	
	ΔMC	ΔLMC	ΔMC	ΔLMC	ΔMC	ΔLMC
RHDIC	.039	.174	.052	.168	.317	.125
RHD4C	.238	.222	.280	.204	.336	.093
RHD12C	.402	.182	.495	.114	.218	.312
TPIC	.041	.158	.140	.136	.378	.086
TP4C	.051	.198	.194	.259	.146	.184
TP12C	.090	.088	.217	.210	.036	.167
TPIC x RHDIC	.204	.220	.235	.215	.358	.136
TP4C x RHD4C	.091	.206	.181	.219	.165	.138
TP12C x RHD12C	.474	.186	.544	.166	.209	.057
RHDMIC	.229	.227	.416	.168	.235	.021
TPMIC	.033	.163	.209	.247	.055	.165
EMCIC			.035	.139	.294	.128
EMC12C	.366	.282	.448	.105	.296	.192
VPDIC	.217	.203	.281	.154	.385	.042
VPD12C	.132	.193	.345	.228	.111	.138
TPMIC x RHDMIC	.063	.185	.283	.221	.074	.125
DL x TPIC x RHDIC	.028	.225	.120	.195	.329	.082
DL x RHDIC	.158	.215	.166	.177	.348	.123
DL x TPIC	.026	.153	.232	.112	.394	.058

TABLE   5

CORRELATIONS REQUIRED FOR SIGNIFICANCE
AT VARIOUS LEVELS OF CONFIDENCE

	No. of Observations	Confidence Level			
		90%	95%	98%	99%
Afternoon					
Forest	46	.248	.298	.356	.396
Wood	88	.178	.213	.254	.282
Plastic	85	.185	.222	.264	.293
Morning					
Forest	42	.259	.312	.374	.417
Wood	68	.204	.244	.291	.324
Plastic	77	.190	.338	.273	.303

Any correlations lower than the above
values are not considered significant
at the specified level of confidence.

TABLE   6

AVERAGE CORRELATION OF SELECTED BASIC WEATHER
VARIABLES BY TIME PERIOD

Time Period	Morning			Afternoon		
	Forest	Wood	Plastic	Forest	Wood	Plastic
I (1)	.365	.215	.251	.367	.312	.418
2	.295	.265	.252	.368	.348	.416
4	.283	.315	.258	.355	.342	.417
6	.285	.328	.251	.350	.322	.442
12	.346	.334	.231	.340	.305	.409
N				.400	.335	.360
I (2)	.434	.291	.254	.439	.337	.413
MI	.402	.404	.232	.429	.385	.448
M2	.400	.414	.237	.448	.385	.448

(1) Average of Six Variables
    (RHD, TP, EMC, VPD, W, TP x RHD)

(2) Average of Four Variables
    (RHD, TP, EMC, VPD)

TABLE   7

LIST OF VARIABLES FROM WHICH SELECTIONS WERE
MADE FOR THE FINAL EQUATIONS
(not in order of selection)

Half day equations (both morning and afternoon)

SAMC	RHDI	TPI	WI	EMCI
VPDI	$RHDI^2$	DL	TPI x RHDI	DL x TPI
TPM	RHM	EMCM	VPDM	RHM x TPM

24 hour afternoon equations (best)

SAMC	RHD4	TP4	EMC4	VPD4
DL	TP4 x RHD4	TPMA	RHDMA	RHDMO
TPMO	EMCMA	VPDMA	EMCMO	VPDMO
W4				

24 hour afternoon equations (instantaneous)

The same 15 variables used for the 12 hour afternoon equations plus:

RHMO	TPMO	VPDMO	RHMO x TPMO

TABLE   8

COEFFICIENT OF DETERMINATION (R^2) USING ONE THROUGH SIX VARIABLES

Site	4th, 5th, 6th Variables	R^2					
		1	2	3	4	5	6
24 hour afternoon - Best							
Forest	EMCMM, RHDMM, TPMM	.656	.857	.890	.912	.916	.918*
Wood	SMC, RHDM, W4	.510	.704	.776	.800*	.800	.800
Plastic	EMC4, WI4, DL	.525	.604	.665	.670	.676*	.679
24 hour afternoon - Instantaneous							
Forest	EMCI, RHMM, RHDI	.656	.827	.864	.882	.890*	.893
Wood	RHM, SMC, RHDI^2	.510	.704	.718	.739	.760	.774*
Plastic	RHM, RHDI^2, TPI x RHDI	.525	.604	.639	.647	.652	.658
8 hour afternoon - Instantaneous							
Forest	DL, RHM x TPM, EMCM	.775	.895	.904	.907	.910*	.912
Wood	VPDM, EMCI, TPI x RHDI	.512	.750	.779	.806	.809	.812*
Plastic	WI, RHM x TPM, VPDM	.522	.604	.615	.623	.626	.650*
16 hour morning - Instantaneous							
Forest	RHM, RHDI^2, DL x TPI	.808	.913	.924	.930	.937	.942*
Wood	EMCI, DL, WI	.487	.602	.648	.660	.679	.687*
Plastic	DL, RHDI^2, WI	.446	.609	.651	.667	.676	.681*

* Indicates lowest (residual mean)^2

Throughout the present study vapor pressure deficit (VPD) was computed with an equation, rather than using tables. The basic equation for VPD is given by Goff and Gratch (1946) as:

$$\log_{10} ew = -7.90298(T_s/T-1) + 5.02808 \log_{10}(T_s/T)$$
$$-1.3816 \times 10^{-7} (10^{11.334(1-T/T_s)}-1)$$
$$+8.1328 \times (10^{-3.49149(T_s/T-1)}-1) + \log_{10} ews$$

where: ew = saturation vapor pressure over a plane surface of

pure ordinary liquid water (mb.)

T = absolute temperature (^{o}K.)

T_s = steam point temperature (373.16^{o}K.)

ews = saturation pressure of pure ordinary liquid

water at steam point temperature

(standard atmosphere = 1013.246 mb.)

In using the Goff-Gratch equation, Kourtz[1] found that one term could be eliminated for practical purposes because of it's small effect on the final values. As a result, the equation used in the present study does not include the next to last term:

$$8.1328 \times (10^{-3.49149(T_s/T-1)}-1)$$

Also, the calculations were made for an elevation of approximately 500 ft. (988.0 mb.)

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[1] Personal Communication (1967)