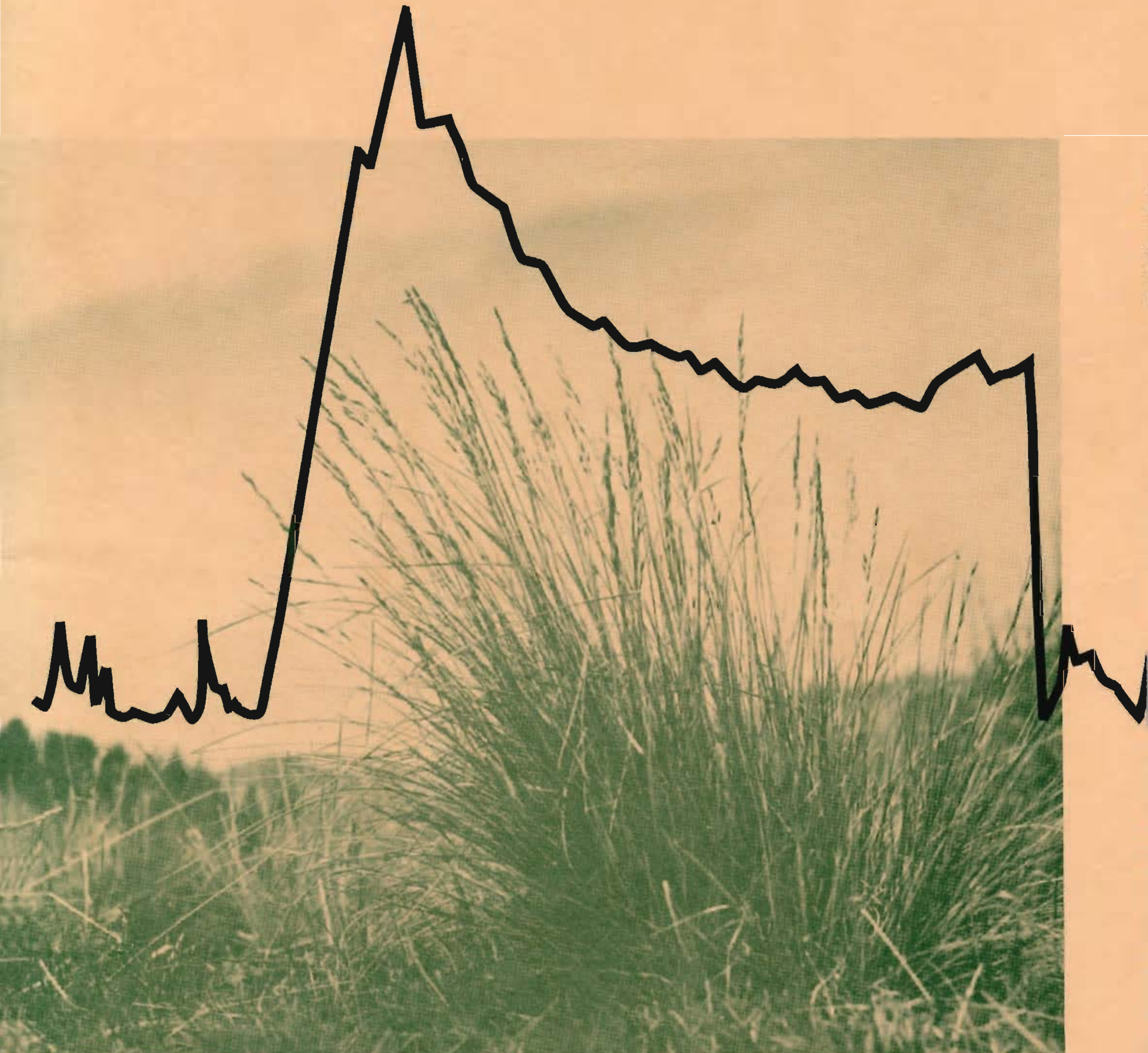
ESTIMATING LIVE FUEL MOISTURE FOR THE 1978 NATIONAL FIRE DANGER RATING SYSTEM

ROBERT E. BURGAN



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RESEARCH SUMMARY

A live fuel moisture model has been developed for the 1978 National Fire Danger Rating System (NFDRS) to provide more analytical and consistent moisture content estimates for herbs, shrubs, and grasses than was available with the 1972 NFDRS. This algorithm replaces the herbaceous vegetation transects used for the 1972 NFDRS.

Weather parameters are used to calculate moisture estimates for annual or perennial herbaceous plants and the leaves and twigs of small woody shrubs. The parameters are daily observations of maximum and minimum relative humidity, maximum and minimum temperature and hours of precipitation duration.

Because plants adapted to different environments respond differently to rainfall anomalies, the United States has been divided into four climate classes to provide a selection of drying rates by climate type (semiarid, subhumid, humid, wet). This permits adjusting seasonal moisture profiles for specific locations.

The amount or load of herbaceous vegetation is transferred between the live and the 1-hour time lag (dead) fuel category as a function of the live herbaceous plant moisture content. This capability utilizes improvements in the mathematical fire spread model that permits living vegetation to act as either a heat sink or a heat source, depending on whether these fuels are ignited in the fire front.

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INTRODUCTION

The specific effect of living herbaceous plants and woody shrubs on fire behavior has been difficult to quantify (Deeming and others 1972). Intuitively we have known that live fuels intercept some of the radiant and convective energy from a fire, thereby interfering with the preheating of adjacent, unburned fuel elements. That is, the live fuels act as a heat sink. The result is a reduction in fire intensity and forward rate of fire spread.

If moisture content is high enough, living fuels will not burn, which in effect reduces the available fuel load. However, as the moisture content of the living fuels decreases, at some point these fuels can be desiccated and ignited within the flaming front, effectively increasing the available fuel load. The live fuels are then no longer a heat sink, but a heat source. Depending on the amount of live material, a rapid and often significant increase in fire intensity and spread can occur (fig. 1). Inclusion of these live fuel moisture effects improves the seasonal response of fire danger ratings.

Phenological processes define the general moisture profile of many plant species during a growing season. This general profile is modified by weather conditions to produce a specific seasonal moisture profile. Thus, particularly with respect to herbaceous fuels, the relative severity of drought can combine with phenological curing processes to produce a seasonal decrease in the live/dead ratio. From a fuels standpoint, curing of herbs and forbs affects the transfer of material from the living to the 1-hour timelag (1-h TL) class in addition to decreasing the moisture content of remaining live plants.

The 1972 National Fire Danger Rating System (NFDRS) (Deeming and others 1972) partially accounted for these effects by using subjective estimates for the condition of two classes of living fuels:

1. Leaves and small twigs of perennial woody shrubs

2. Herbaceous plants.

The following section briefly reviews how these estimates were made and some problems that resulted.

LIVE FUEL MOISTURE ESTIMATION — 1972 NFDRS

Woody Fuels

Only general levels of moisture in the twigs and foliage of living woody plants were considered in the 1972 NFDRS. The moisture levels varied according to three subjectively assigned growth stages, (Deeming and others 1972) but the loading of live woody fuels remained constant.

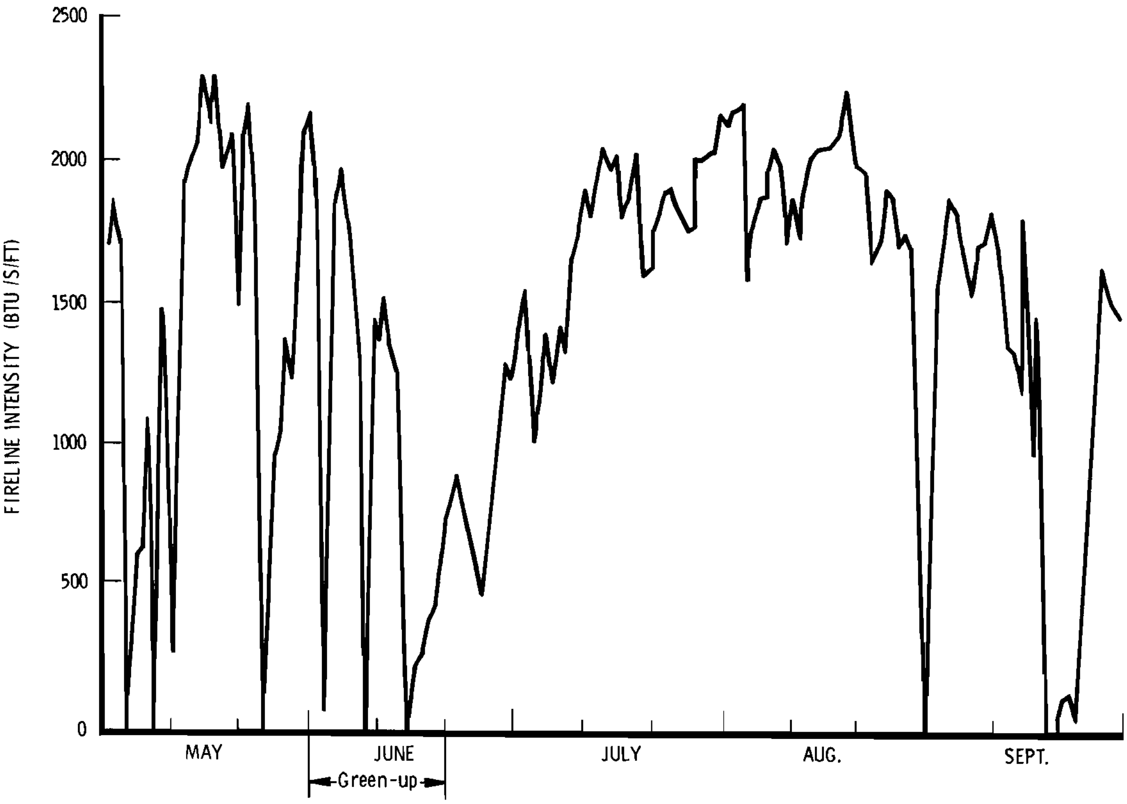

Figure 1.--This example for Libby, Montana, 1973, illustrates the fireline intensity for fuel model C with perennial grass (live/dead ratio 0.5). Intensity decreased markedly during the green-up period in the first three weeks of June, then increased again as the live herbaceous fuel moisture decreased during the summer.

Herbaceous Fuels

Living herbaceous fuels were assumed to have a constant moisture content in the 1972 NFDRS; however, the proportion of living herbaceous fuel varied. Range forage transects were used to estimate percentage of the fine fuels by volume that consisted of live herbaceous material. There were several disadvantages with this subjective procedure:

1. Transect location was critical. Microtopography produced significant differences in conditions between transects in close proximity.

2. Percent-green estimates made by different observers on a single transect were not consistent.

3. Important changes in the condition of herbaceous fuels were not necessarily observed or reported at appropriate times.

Fire danger ratings were particularly sensitive to percent-green estimates.

Although the 1972 NFDRS would respond reasonably well to properly reported changes in live fuel conditions, it had limitations.

1. Living fuels always acted as a heat sink, never a heat source.

2. A constant moisture content was assumed for the herbaceous fuels, but the live/dead ratio changed.

3. The quantity live of woody fuels was held constant, but the moisture content changed according to the growth stage assigned.

Thus, living woody fuels and herbaceous fuels were not treated similarly.

Improvements in the fire model used in the 1978 NFDRS made it possible to treat live fuels more realistically. The result was that live fuels could act as a heat sink or as a heat source. The live fuels became a heat source when their moisture content became so low that they could be desiccated and ignited during combustion of the dead fuels. However, if the moisture content was above some critical level, live fuels would not burn, but rather would act as a heat sink (Albini 1976).

The live fuel moisture model was developed to provide more analytical and consistent estimates of live fuel moisture at a time when capability to use this information had improved.

THE LIVE FUEL MOISTURE MODELS — 1978 NFDRS

The live fuel moisture model was developed to replace the herbaceous vegetation transects used in the 1972 NFDRS. Although it is not rigorously based on principles of plant physiology, the model does provide a broadscale approximation of the moisture content of living herbaceous plants, leaves, and twigs of small woody shrubs.

In the original live fuel model proposed by Rothermel,[1] plant moisture was determined as a function of the Keetch-Byram Drought Index. However, several empirical factors required to control plant response to drying and wetting could not be derived for all climates of the United States.

During development of the 1978 NFDRS, we noticed the 1000-hour timelag (1000-h TL) fuel moisture developed by Fosberg and others[2] responded to wetting and drying cycles similar to that expected for the live fuels. Thus, with some modifications, the 1000-h TL fuel moisture now serves as the basic meteorological filter for calculating live fuel moistures.

Plants adapted to different moisture regimes respond differently to rainfall anomalies. Those adapted to a moist environment will lose moisture faster during drought than those from a dry environment. An essential feature of the live fuel moisture model used in the 1978 NFDRS is a selection of drying rates by climate type or class.

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[1]Rothermel, Richard C. (n.d.) Live fuel moisture model. Manuscript in preparation. Northern Forest Fire Laboratory, Missoula, Mont.

[2]Fosberg, Michael A., Richard C. Rothermel, and Patricia L. Andrews. (n.d.) Moisture content calculations for the 100- and 1000-hour timelag fuels in fire danger rating. Manuscript in preparation. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

The United States can be divided into many climatic zones; but four climate classes were enough to provide the broadscale plant moisture responses needed for rating fire danger. These four climate classes were adapted from Thornthwaite's earliest climate classification system (Thornthwaite 1931). His arid and semiarid provinces were grouped into Climate Class 1 because the true desert is of little real concern to fire management. Also, in terms of fire behavior, the subhumid province groups better with the humid province than with the dry, subhumid province. The climate class descriptions, the general geographic areas to which they apply, and the vegetation characteristic to each, are provided in table 1. Figure 2 shows the general locations to which the climate classes apply.

Table 1.--*Climate class selection guide*[3]

NFDRS climate class	Thornthwaite[4] humidity province	Characteristic vegetation	Regions
1	Arid	Desert (sparse grass and scattered shrubs)	Sonoran deserts of west Texas, New Mexico, southwest Arizona, southern Nevada, and western Utah; and the Mojave Desert of California
	Semiarid	Steppe (short grass and shrubs)	The short grass prairies of the Great Plains; the sagebrush steppes and pinyon/juniper woodlands of Wyoming, Montana, Idaho, Colorado, Utah, Arizona, Washington, and Oregon; and the grass steppes of the central valley of California
2	Subhumid (rainfall deficient in summer)	Savanna (grasslands, dense brush and open conifer forests)	The Alaskan interior; the chaparral of Colorado, Arizona, New Mexico, the Sierra Nevada foothills, and southern California; oak woodlands of California; ponderosa pine woodlands of the West; and mountain valleys (or parks) of the Northern and Central Rockies
3	Subhumid (rainfall adequate in all seasons)	Savanna (grasslands and open hardwood forests)	Blue stem prairies and blue stem-oak-hickory savanna of Iowa, Missouri, and Illinois
	Humid	Forests	Almost the entire Eastern United States; and those higher elevations in the West that support dense forests
4	Wet	Rain forests (redwoods, and spruce-cedar-hemlock)	Coast of northern California, Oregon, Washington, and southeast Alaska

[3]Deeming and others 1977.
[4]Thornthwaite 1931.

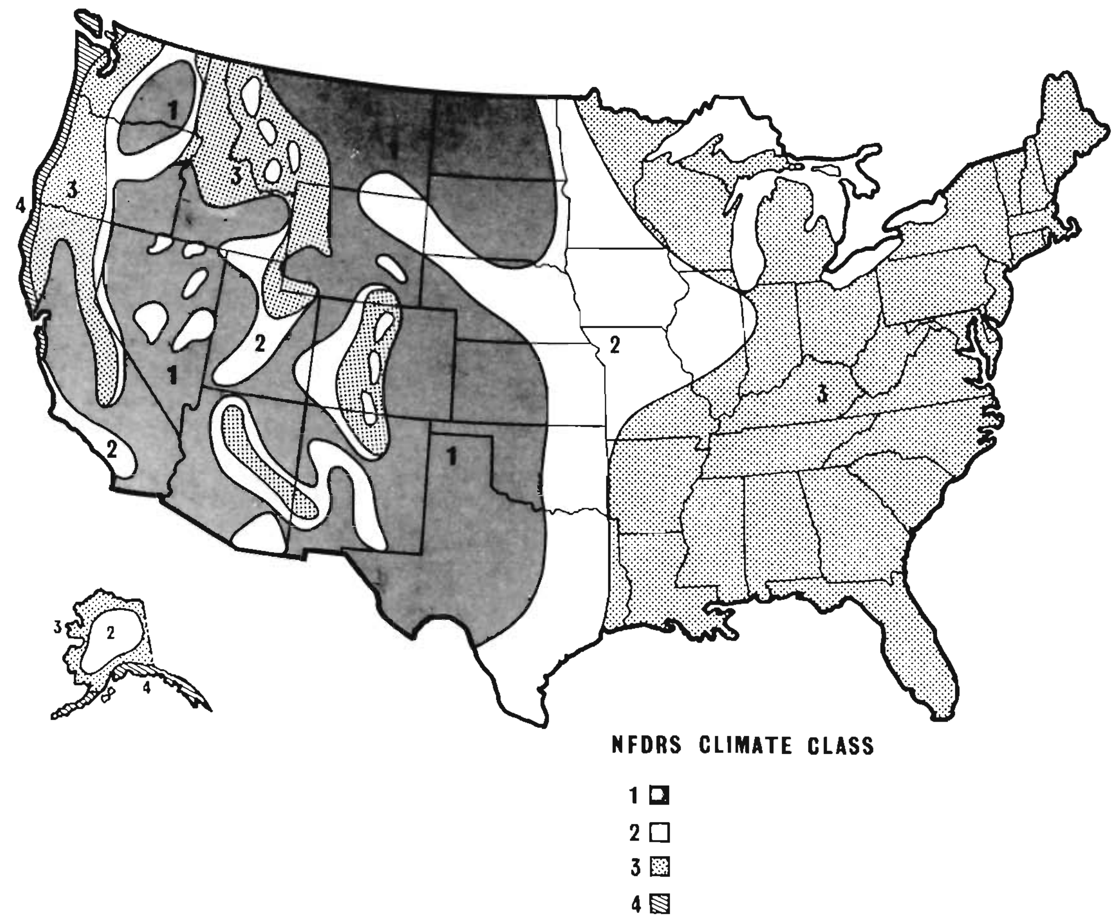

Figure 2.--Map of the United States showing the general locations of the NFDRS climate classes (Deeming and others 1977).

Different linear drying rates are defined by climate class for annuals, perennials, and woody plants. But within a particular climate class, a single drying rate is assumed for live woody plants throughout a growing season. For live herbaceous plants, drying occurs in two stages--green stage when the herbaceous moisture is above 120 percent, and transition stage for moistures between 120 percent and 30 percent. In the green stage, both annuals and perennials dry at the same rate. But in the transition stage, the drying rate is faster for annuals than for perennials.

To define the drying rates, the endpoints of the drying curves were required. Weather data from several locations within each climate class were used to plot seasonal 1000-h TL fuel moisture profiles. Then typical plant moistures for each climate class and vegetation type (woody, annual, perennial) were matched with these profiles. Because measurements of seasonal moisture variation in woody and herbaceous plants were not generally available from different parts of the United States, the live fuel model was calibrated to produce reasonable moisture values. Performance objectives are shown in table 2.

Table 2.--*Minimum moisture content for live fuels*

Type of season	Grasses and forbs		Shrubs, twigs, and foliage
	Annuals	Perennials	
	Percent		
Wet	∿30 (Late cure)	>80	>110
Normal	<30 (Normal cure)	50-80	80-100
Dry	<30 (Early cure)	<50	50-80

The highest live fuel moistures were defined to be 250 percent for the herbaceous fuels and 200 percent for the live woody shrubs at a 25 percent 1000-h TL fuel moisture. At the lower end of the moisture scale, herbaceous plants were considered cured at 30 percent moisture content and woody plants dead or dormant if their moisture content dropped to 50 percent. The minimum woody and herbaceous moistures were matched with typical minimum 1000-h TL moistures and X1000 values, respectively, for each climate class. The slopes and intercepts of the drying curves for each climate class are provided in table 3.

The live fuel moisture algorithm gives the fuel models a dynamic character by simulating the curing of the herbaceous fuels. This is accomplished by transferring fuel load from the live herbaceous class to the 1-h TL class as herbaceous fuel moisture drops below 120 percent during the growing season.

Table 3.--*Slopes and intercepts for the drying rates of the live fuel models*

Climate Class	Woody Fuels		Herbaceous Fuels					
			Annuals and Perennials Green Stage		Annuals Transition Stage		Perennials Transition Stage	
	Slope	Intercept	Slope	Intercept	Slope	Intercept	Slope	Intercept
1	7.5	12.5	12.8	-70.0	18.4	-150.5	7.4	11.2
2	8.2	-5.0	14.0	-100.0	19.6	-187.7	8.3	-10.3
3	8.9	-22.5	15.5	-137.5	22.0	-245.2	9.8	-42.7
4	9.8	-45.0	17.4	-185.0	24.3	-305.2	12.2	-93.5

General Model Development

Rothermel[1] provided the empirical data used for development and initial testing of the live fuel moisture model. He used the xylene distillation technique of determining moisture content to construct profiles of herbaceous and woody plants near Missoula, Mont., during the 1975 and 1976 fire seasons. The live fuel model was initially developed to emulate these moisture profiles, then adjusted to produce reasonable moisture profiles for the remainder of the United States.

Herbaceous Fuel Moisture

Moisture Computations - The live herbaceous fuel moisture (HFM) is a function of a modified 1000-h TL fuel moisture called the X1000 value, which is a function of the daily change in the 1000-h TL fuel moisture. The original effort to relate herbaceous fuel moisture directly to the 1000-h TL fuel moisture proved reasonable during periods of drying, but it produced excessive herbaceous fuel moisture recovery during periods of precipitation. Therefore, the X1000 value was designed to decrease at the same rate as the 1000-h TL fuel moisture, but have a slower rate of increase.

During the growing season the X1000 value is calculated as:

$$X1000 = YX1000 + K_1 K_2 (\Delta MC1000)$$

where: YX1000 = yesterday's X1000 fuel moisture

K_1 = drying or wetting factor

K_2 = temperature factor

ΔMC1000 = 24 hour change in the 1000-h TL fuel moisture

If $\Delta MC1000 < 0$ (drying) $K_1 = 1$

If $\Delta MC1000 \geq 0$ (wetting) $K_1 = 0.0333X + 0.1675$ subject to

$$0.5 \leq K_1 \leq 1.0$$

If average temperature >50°F (10°C) $K_2 = 1.0$

If average temperature <50°F (10°C) $K_2 = 0.6$

K_1 limits the increase in herbaceous fuel moisture due to precipitation. It is scaled to allow the X1000 value to respond the same as the 1000-h TL fuel moisture when the 1000-h TL fuel moisture is 25 percent or more.

K_2 reduces the response of the X1000 value to compensate for slower physiological processes in plants during cool weather. Figure 3 compares the 1000-h TL moistures with the X1000 value.

Prior to spring greenup, the herbaceous fuel is assumed to be completely cured, so the herbaceous fuel moisture (HFM) is equal to the 1-h TL fuel moisture.

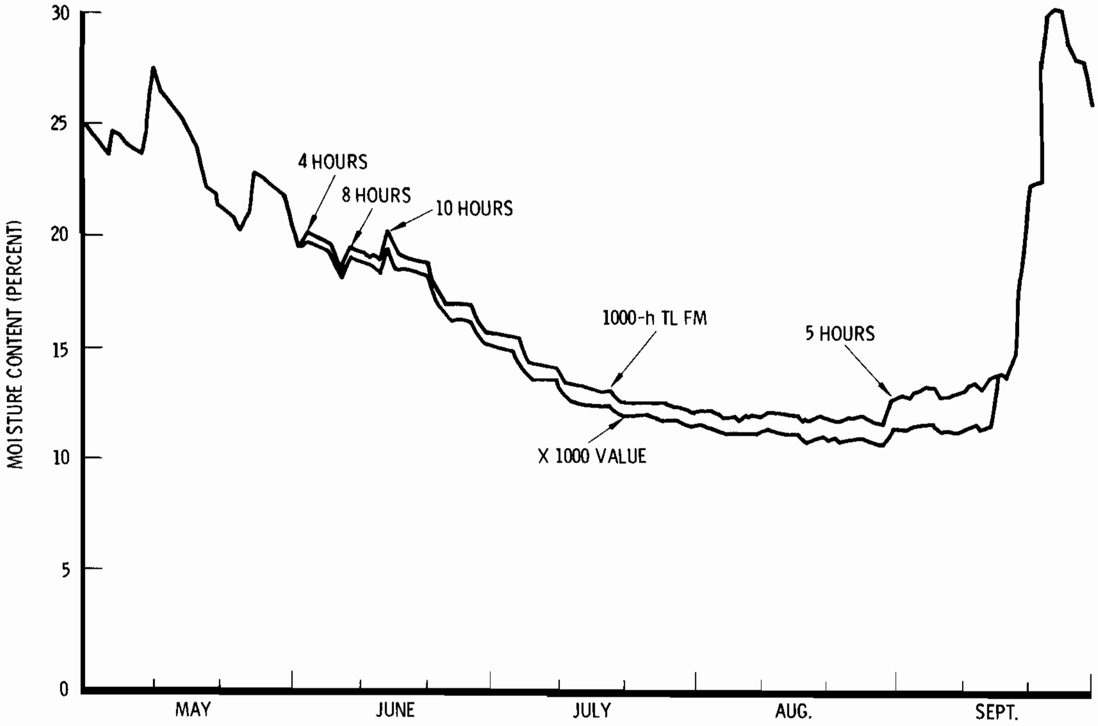

Figure 3.--Comparison of the X1000 value with the 1000-h TL fuel moisture computed from weather data recorded at Libby, Mont. 1973. Hours of precipitation for the four significant rainfall events are indicated.

During spring greenup, the live herbaceous fuel moisture increases gradually from the 1-h TL fuel moisture. A gradual greenup was built into the live fuel model at the request of users in the Eastern United States who feared that the "instantaneous" greenup originally proposed would not properly reflect the transition from high fire danger in early spring to low fire danger in summer. The length of the greenup period varies from 7 days for climate class 1, to 28 days for climate class 4. The length of the greenup was scaled to the climate class because plants growing in drier climates typically respond quicker to favorable growing conditions than do plants in wetter climates.

When a spring flush of growth becomes generally apparent, the user specifies the beginning of greenup. Then the herbaceous fuel moisture is calculated according to the equation:

HFM = FM1 + [(HERBGA + HERBGB * X1000) - FM1] * GREN

where:

HERBGA, HERBGB = climate dependent intercept and slope for annuals or perennials from table 3

X1000 = X1000 value

GREN = fraction of the greenup period that has elapsed.

FM1 = moisture content of the 1-h TL fuel.

If a second greenup occurs during a growing season, the X1000 value is again set equal to the 1000-h TL fuel moisture, and the same greenup procedure is followed, except the herbaceous moisture increases from its current value instead of the 1-h TL FM.

After the greenup period is complete, (GREN = 1.0) the herbaceous fuel moisture is calculated from:

$$HFM = HERBGA + HERBGB * X1000$$

until the user specifies that the herbaceous vegetation has cured phenologically, or frozen.[5] Then the herbaceous fuel moisture is again equal to the 1-h TL fuel moisture.

Figure 4 illustrates the relationship between the X1000 value and the annual and perennial herbaceous moistures.

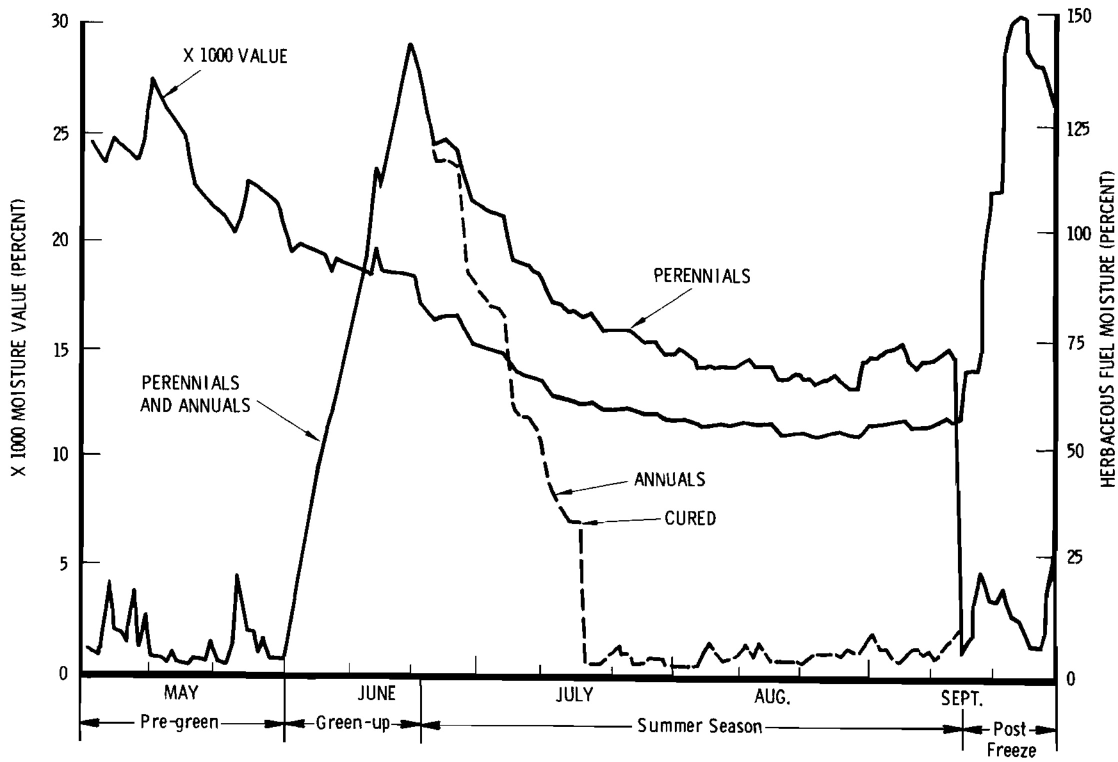

Figure 4.--An example of the relationship between the X1000 VALUE, and calculated moisture content of annual and perennial herbaceous plants. All herbaceous moisture follows the 1-h TL fuel moisture before green-up and after curing or freezing.

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[5]"Green, cured" and "frozen" are always specified manually by AFFIRMS users. But in FIRDAT, which is used to process historical data, the user defines a date after which a freeze is possible. The specific date of the freeze is defined by one of two "freezing" criteria:

1. Five days (nonconsecutive) with a minimum temperature $\leq$ 32°F (0°C)
2. One minimum temperature $\leq$ 25°F (-4°C)

Transfer of Fuel Between Live and Dead Categories - All the herbaceous fuel load is included in the 1-h TL fuel load before greenup. During greenup, the live herbaceous fuel load is transferred from the 1-h TL to the live fuel category as the herbaceous moisture increases from 30 percent to 120 percent. The herbaceous fuel load is at its maximum and the 1-h TL fuel load at its minimum when the herbaceous moisture is greater than 120 percent.

As herbaceous plant moisture decreases later in the growing season, the load of *perennial* herbaceous fuels is shifted between the live and dead fuel categories as its moisture varies between 120 percent and 30 percent. This is the transition stage; 120 percent is an approximate value, serving as the upper limit for transition because it roughly defines the moisture content at which new growth is complete and the foliage is mature. Thirty percent was defined as the minimum moisture for transition because that is the approximate fiber saturation point, below which herbaceous plants are assumed to be dead.

For *annual* herbaceous plants, the process differs slightly. After greenup, the moisture content of annuals is *not* allowed to increase, so the fuel load for annuals then transfers from the live category to the dead category; never in the reverse direction as allowed with perennials. At 30 percent moisture content, all the herbaceous fuels have been added back into the 1-h TL class, i.e., after phenological curing or after a freeze in the fall.

The fuel load transfer equations are:

$$W1DP = W1D + WHERB * FCC$$

$$WHERBC = WHERB * (1.0 - FCC)$$

where: $FCC = -0.0111 * HFM + 1.33$ and $0 \leq FCC \leq 1.0$

and W1DP = total load of 1-h TL fuel, including dead herbaceous fuel transferred to the 1-h TL category

W1D = load of the 1-h TL fuel before inclusion of any cured herbaceous material

WHERB = total load of herbaceous fuel

FCC = fraction of the herbaceous fuel that is to be transferred to the 1-h TL class

WHERBC = load of herbaceous fuel that is still green

HFM = herbaceous fuel moisture

Figure 5 shows herbaceous fuel load changes in relation to moisture content changes.

LIVE FUEL MODEL

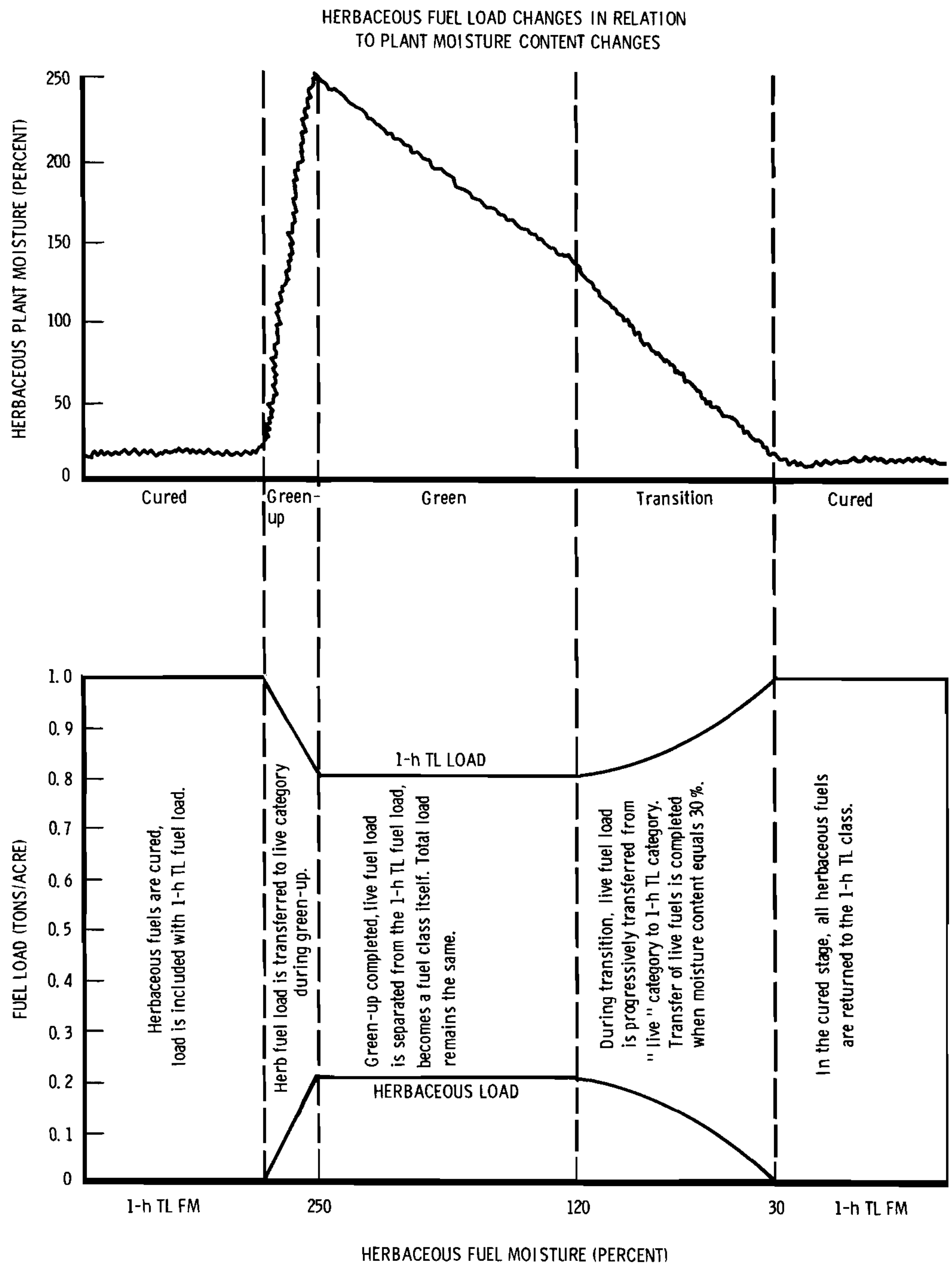

Figure 5.--Herbaceous fuel load changes between living and 1-h TL categories in relation to herbaceous moisture content.

Figures 6 and 7 illustrate examples of the transfer of fuel between the live and dead categories for perennial and annual grasses. Typically, herbaceous moisture will be somewhere near 250 percent at the completion of greenup. But these examples illustrate that given a dry spring or late greenup, the herbaceous moisture will peak at a lower value.

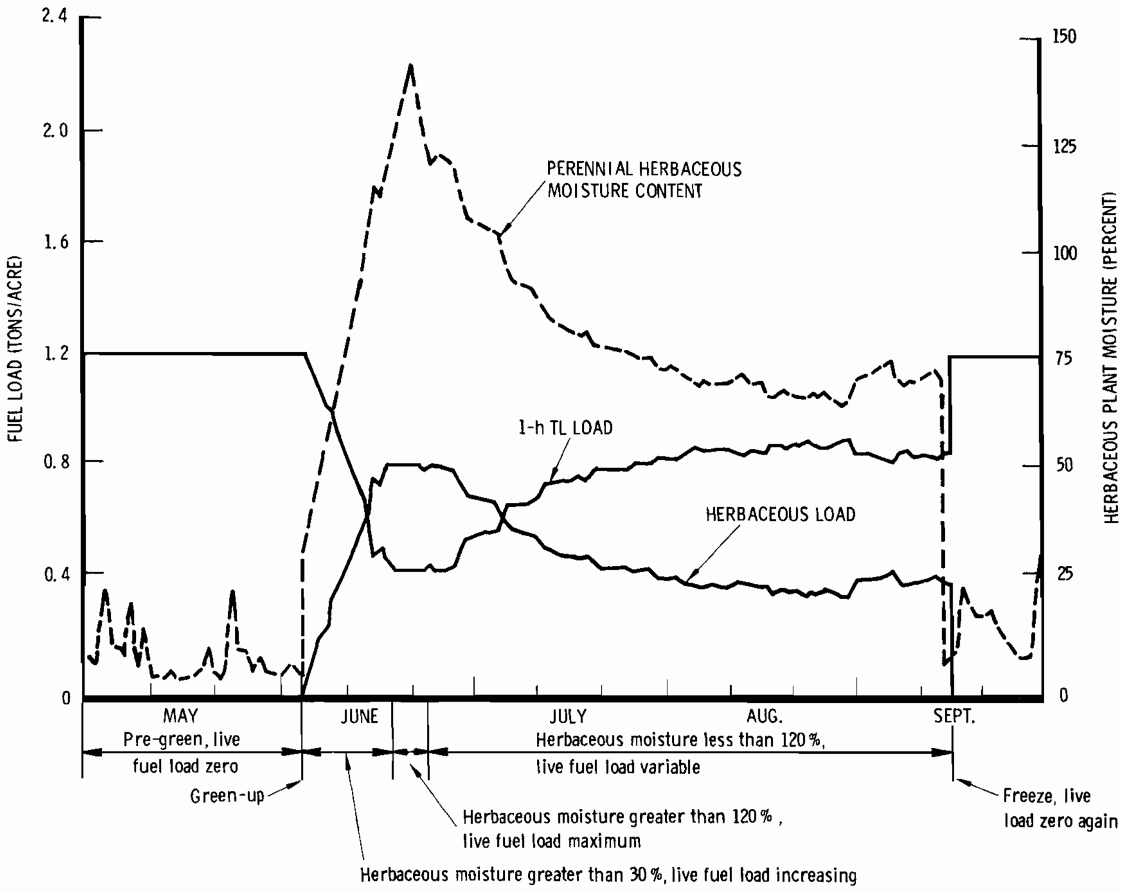

Figure 6.--The moisture content of live plants controls the transfer of fuel load between dead (1-h TL) and live herbaceous categories. The slope assigned to perennials prevents a complete transfer of fuel load from live to the 1-h TL category until a freeze occurs.

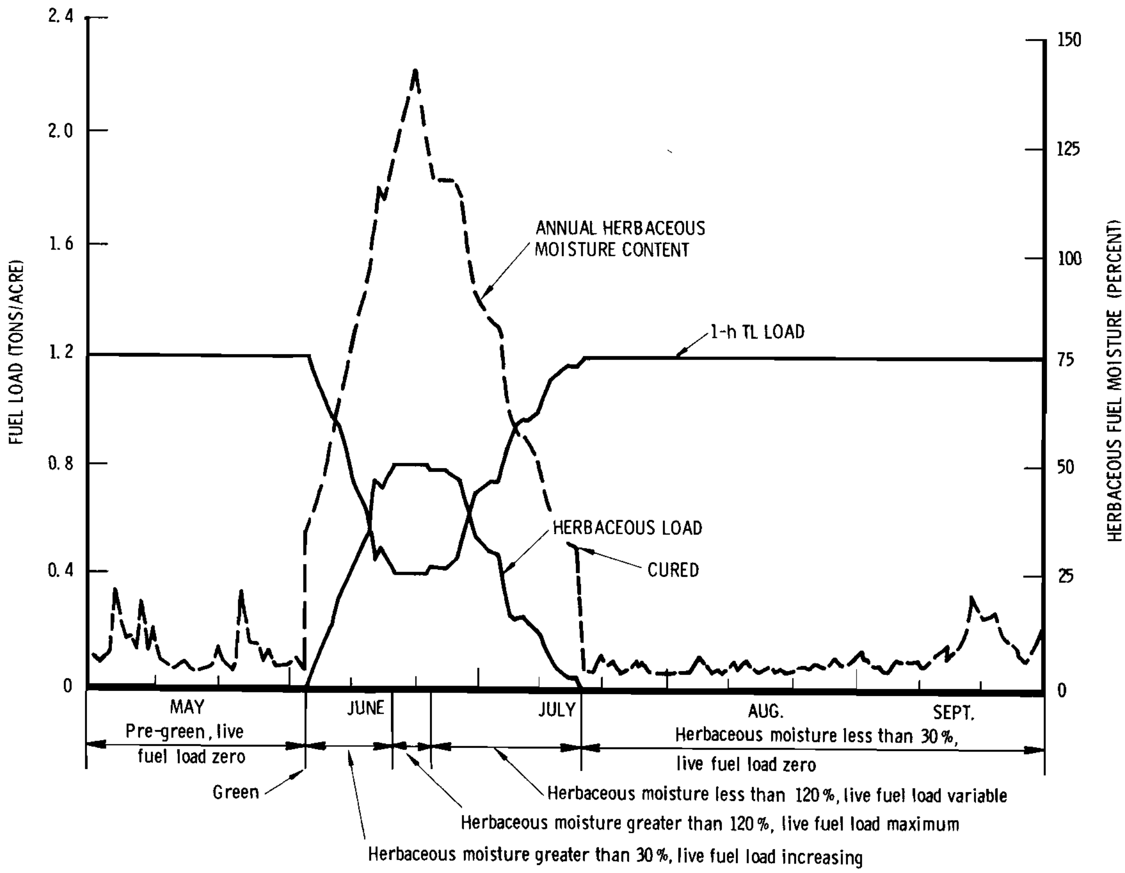

Figure 7.--After greenup is complete, the fast drying rate assigned to annuals results in a rapid transfer of fuel load from the live herbaceous to the 1-h TL category.

Woody Fuel Moisture Model

Prior to greenup in the spring, woody shrubs are assumed to be dormant, so the woody fuel moisture (WFM) is held constant. Measurements of chamise leaf moisture in southern California (Dell and Philpot 1965) indicate minimum values for woody plants in climate class 2 is about 60 percent. Likewise, measurements in the southeast (Blackmarr and Flanner 1968) suggest a minimum woody moisture of 70 percent for climate class 3. So depending on the climate class, pregreen WFM values are defined as 50, 60, 70, or 80 for climate classes 1, 2, 3, or 4 respectively. During spring greenup, woody moisture gradually increases from the pregreen minimum according to the equation:

WFM = PREGRN + [(WOODA + WOODB * MC1000) - PREGRN] * GREN

where: PREGRN = pregreen minimum moisture

WOODA, WOODB = climate dependent intercept and slope from table 3

MC1000 = 1000-h TL fuel moisture

GREN = fraction of the greening-up period that has elapsed

If a second green-up occurs during a growing season, the woody fuel moisture increases from its current value instead of from the pregreen value.

After greenup is complete, (GREN = 1.0) the woody fuel moisture is calculated from:

WFM = WOODA + WOODB * MC1000

until the shrubs become dormant. At that time the woody fuel moisture is set back to the minimum value specified by the climate class. Figure 8 illustrates a typical woody fuel moisture profile and its relation to the 1000-h TL fuel moisture.

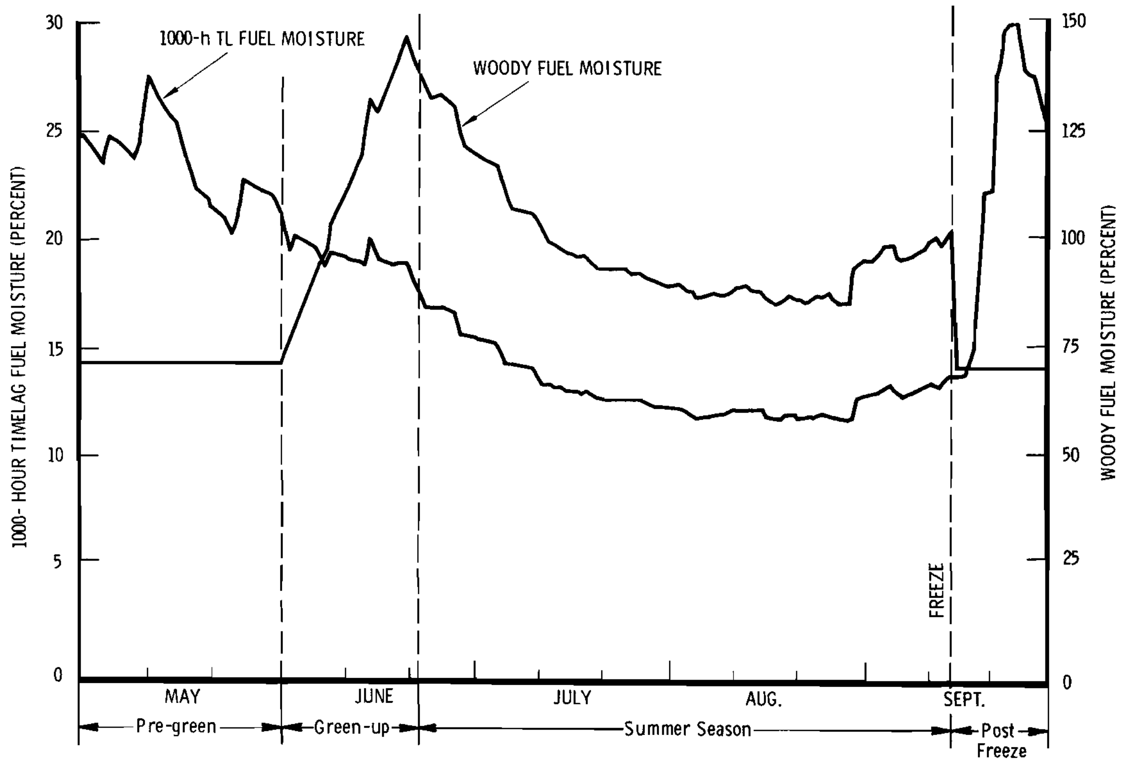

Figure 8.--Typical woody fuel moisture profile and its relation to the 1000-h TL fuel moisture.

APPLICATION OF THE LIVE FUEL MOISTURE MODEL

To apply the live fuel model, the following conditions must be met:

(1) Weather observations must be started 3 to 4 weeks prior to the onset of greenup. This assures that the 1000-h TL fuel moisture has stabilized at a reasonable value for current weather conditions.

(2) Greenup must be defined at the proper time

(3) Herbaceous plants must be correctly designated as annuals or perennials.

(4) Climate class must be selected. The climate class should be selected for the location of the weather station. The choice of climate classes compensates for a lack of local live fuel moisture data.

The user has the capability to "tune" the live fuel model to produce live woody and herbaceous moisture profiles that are reasonable for his area. This can be done by designating herbaceous plants as annuals or perennials, and selecting the proper climate class.

Selection of Annual or Perennial Designation for Herbs and Forbs - Although the moisture content of annuals does not increase after greenup is complete, the live fuel model does assign the same *drying* rate to both annuals and perennials at moisture contents above 120 percent. During transition (HFM between 120 percent and 30 percent); however, annuals dry at a much faster rate than perennials. Thus, the live fuel model typically indicates a curing of annuals sometime during the summer season, but perennials do not cure until a freeze occurs. The annual designation should be used only if *more than half* of the herbaceous plants are annuals.

Selection of Climate Class - The user can affect live fuel moisture estimations through his selection of climate class. The effect of climate class selection on the moisture profile for perennial herbaceous grass is shown in figure 9. Climate class 3 is the proper selection for this data set. Normally, it is useful to test only one climate class above or below the one that is estimated to be appropriate for a particular fire weather station.

These controls provide the user with a great deal of flexibility to "tune" the live fuel model until it provides realistic moisture profiles for his area.

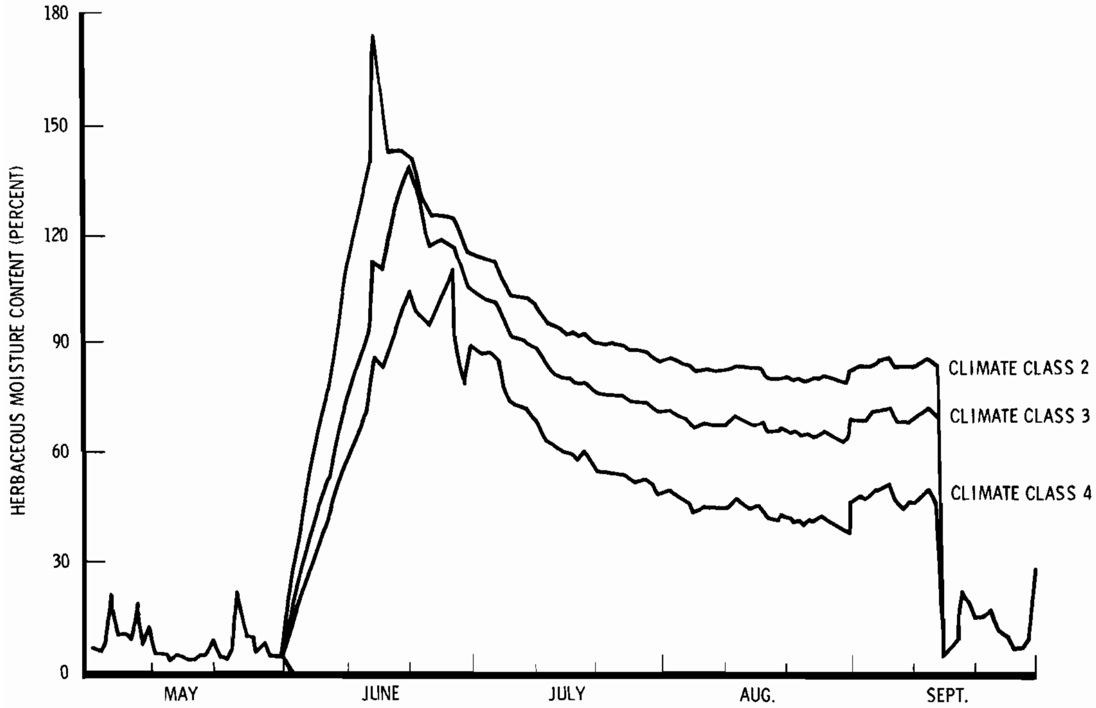

Figure 9.--Given the same weather, faster drying rates for higher numbered climate classes produce lower live fuel moistures for perennial herbaceous plants. Similar results would be obtained for annuals, with climate class 4 producing the earliest date of curing. Climate class 3 was the correct choice for this station.

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