# Chapter 11

# WEATHER AND FUEL MOISTURE

The moisture content of live and dead vegetation is not in itself a weather element. It is a product, however, of the cumulative effects of past and present weather events and must be considered in evaluating the effects of current or future weather on fire potential. Fuel moisture content limits fire propagation. When moisture content is high, fires are difficult to ignite, and burn poorly if at all. With little moisture in the fuel, fires start easily, and wind and other driving forces may cause rapid and intense fire spread. Successful fire-control operations depend upon accurate information on current fuel moisture and reliable prediction of its changes.

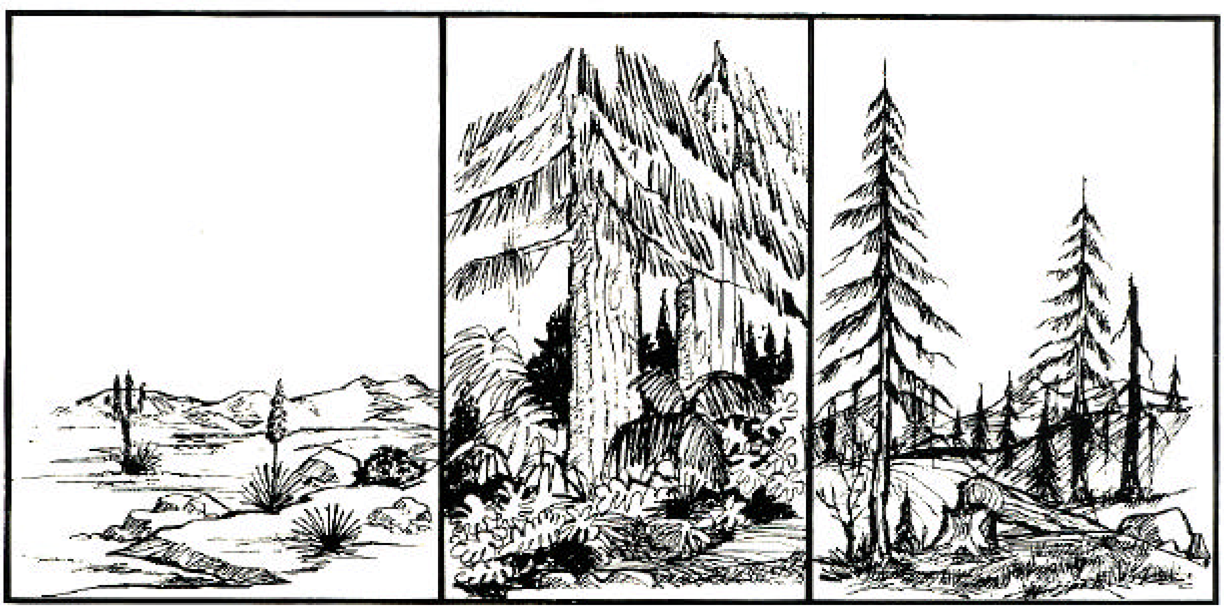
The determination of exact fuel-moisture values at any time is complicated by both the nature of the fuels and their responses to the environment. Fuel moisture changes as weather conditions change, both seasonally and during shorter time periods. This fact, coupled with known attributes of different fuels, provides a useful basis for estimating fire potential in any forest or range area. This chapter describes some of the more important relationships involved.

## WEATHER AND FUEL MOISTURE

In fire-control language, fuel is any organic material—living or dead, in the ground, on the ground, or in the air—that will ignite and burn. Fuels are found in almost infinite combinations of kind, amount, size, shape, position, and arrangement. The fuel on a given acre may vary from a few hundred pounds of sparse grass to 100 or more tons of large and small logging slash. It may consist of dense conifer crowns over heavy and deep litter and duff, or may be primarily underground peat. There is even the "urba-forest," an intimate association of wild-land fuels and human dwellings. Any one composite fuel system is referred to as a **fuel complex.**

Every fuel complex has an inherent built-in flammability potential. The extent to which this potential may be realized is limited largely by the amount of water in the fuel, but fuel moisture is a continuous variable controlled by seasonal, daily, and immediate weather changes.

For convenience, the amount of water in fuel is expressed in percentage, computed from the weight of contained water divided by the ovendry weight of the fuel. Fuel-moisture values in the flammability range extend from about 35 percent to well over 200 percent in living vegetation, and about 1.5 to 30 percent for dead fuels. Remember that living-fuel moisture is primarily the moisture content of living foliage, while dead-fuel moisture is the moisture in any cured or dead plant part, whether attached to a still-living plant or not. Living and dead fuels have different water-retention mechanisms and different responses to weather. Hence, we will discuss them separately before considering them together as a single fuel complex.



**Where vegetation is plentiful, fire potential depends largely upon moisture content. The rain forest may be fire-safe virtually al the time, while the parched forest at times may be explosive.**

Water in living plants plays a major role in all plant life processes. It transports soil nutrients from the roots up through conducting tissues to the leaves. In the leaves, some of the water becomes raw material from which the organic materials are manufactured for plant growth; some water transfers the manufactured products to growing tissues and storage points; and finally, some water is transpired through leaf pores to become water vapor in the atmosphere.

## Seasonal Changes

The moisture content of living-plant foliage of wildland species varies markedly with seasonal changes in growth habits except in humid southern climates. These changes are usually typical for the local species and climate, but are tempered in timing by deviations from normal weather, such as amount and spacing of precipitation, date of disappearance of snow-pack, or the occurrence of unseasonably warm or cool temperatures. Thus, the beginning or ending dates of growth activity affecting plant moisture may vary 2 weeks or more, and the growth activity may vary during the season.

Growing seasons are longest in the lower latitudes and become progressively shorter toward higher latitudes. They may be as short as 60 days at the northern forest limits. Elevation and aspect affect local microclimate and produce local differences in seasonal development of many plant species. In mountain topography, for example, lower elevations and southern exposures favor the earliest start of the growing season. Moisture content of all new foliage is highest at the time of emergence. Moisture content two or three times the organic dry weight is common. The period of emergence varies according to localities, species, and local weather. The peak moisture normally declines quite rapidly during leaf growth and development, then somewhat more slowly to a terminal value leading to death or dormancy in the fall. In annual plants, the end result is the death of the plant; in deciduous shrub and tree species, the end result is the death of the foliage, while in evergreens some leaves live and others die and fall.

In organic (peat or muck) soils, the excessive demand for moisture to support leaf emergence can result in soil desiccation and in high fire danger if soils are burnable. This problem ceases when normal evapotranspiration is established.

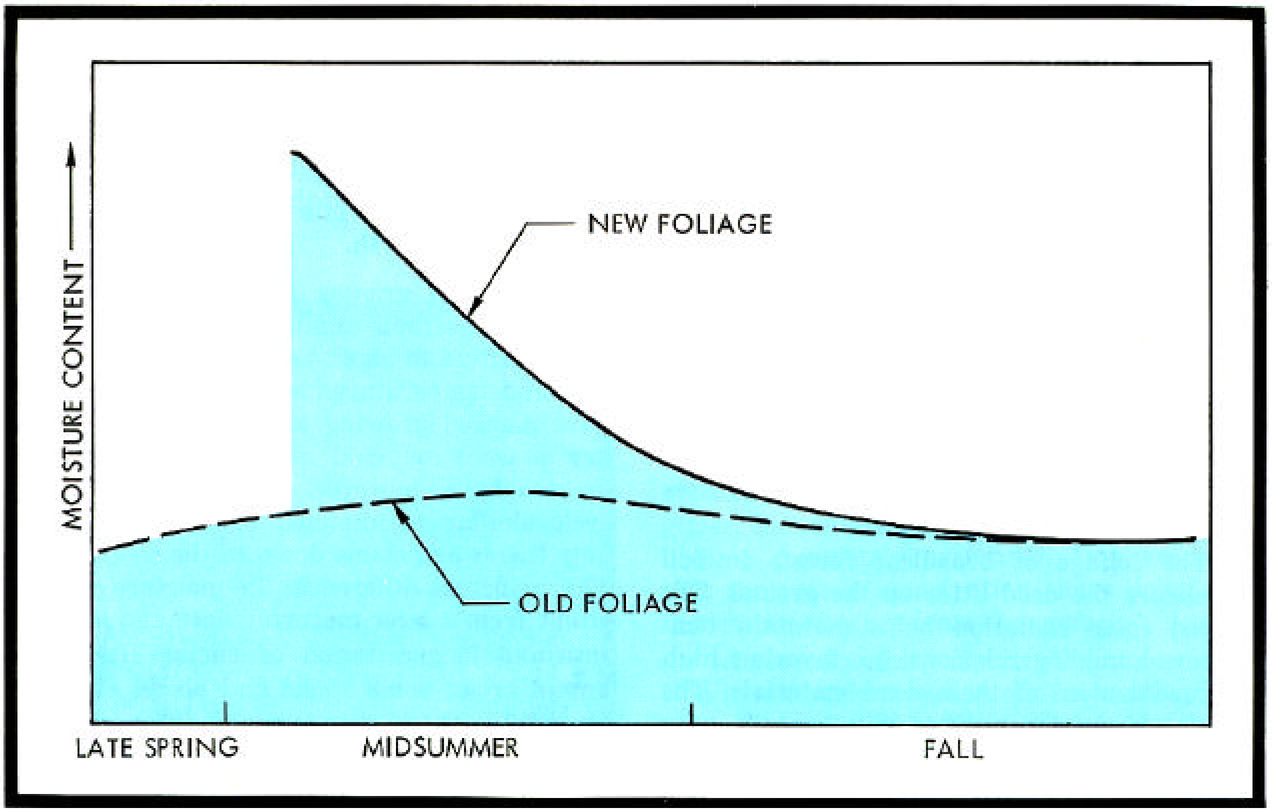
The decrease in plant foliage moisture is usually not smooth, but an irregular succession of ups and downs. These irregularities may result from one or more causes, including periodic changes in food-manufacturing demands, changes in weather, and variations in available soil moisture. Within the individual leaf, however, moisture is maintained within tolerable limits during the growing season through ability of the leaf to open or close the leaf pores and thus regulate the rate of transpiration to the atmosphere. Foliage moisture content may even change during the course of the day.

## Effect of Type

### *Evergreens*

Evergreens growing in climates having marked seasonal changes generally have seasonal growth cycles. Leaves that have lived through a dormant period increase in moisture content at the beginning of the new season from a minimum of perhaps 80-100 percent to a maximum of perhaps 120 percent within a few weeks. These values are typical, but do not necessarily apply to all species and regions. Moisture decreases slowly after this modest increase until the minimum is again reached at the onset of dormancy.

Within a few days of the initial increase in moisture in old leaves, twig and leaf buds open and a new crop of leaves begins to emerge. Their initial moisture may exceed 250 percent. Leaves may emerge quickly, or over an extended period, depending on species and the character of the weather-related growing season. The average moisture content of the new growth drops rapidly to perhaps 150 percent, as the new leaves grow in size until about midsummer, and then more slowly, matching the moisture content of the older foliage near the end of the growing season.




**The moisture content of old foliage changes only slightly during the season, while that of new foliage is very high at emergence and then drops, first rapidly, then more slowly, matching that of the old foliage at the end of the growing season.**

Different species of evergreen trees and shrubs characteristically retain a season's crop of foliage for different periods of years. This may vary among species from one season to five or more. There are also differences within species, due partly to age, health, and stand density, but mostly to the weather-dictated character of the growing season. Thus, in years of poor growth there is normally little leaf fall, and in years of lush growth the fall is heavy. As crown canopies become closed, leaf fall tends to approximate foliage production. The oldest foliage, that closest to the ground, is the first to fall, and, in time, the lower twigs and branches that supported it must also succumb and add to the dead fuel supply.

There are exceptions, of course, to the normal, seasonal growth and leaf-moisture cycle, and to the annual replenishment of foliage. Particularly striking are the variations found in the drought-resistant brush and chapparral species in the semiarid West. It is not uncommon for midseason soil-moisture deficiency to cause cessation of growth in these species, with foliage moisture lowering to between 40 and 50 percent. Usually, these plants retain the ability to recover after the next rain. Prolonged severe drought, however, can prove fatal to major branches or even to whole shrubs. Conflagration potential is then at its peak.\

The live foliage of evergreens as a class is usually more combustible than that of deciduous species. There are several reasons, but differences in their moisture regimes are most important, All deciduous foliage is the current year's growth, and it maintains relatively high moisture content during most of the growing season. Evergreens, on the other hand, and particularly those that retain their foliage for a number of years, have much lower average foliage moisture during the growing season. Old-growth foliage with its lower moisture may constitute 80 percent or more of the total evergreen foliage volume. Among the evergreens, too, there is greater tendency toward a mixture with dead foliage, branches, and twigs.

### *Deciduous Species*

In contrast to the evergreens, all deciduous species contribute each year's total foliage production to the surface dead fuel accumulation. During the process of production and decline, however, there are considerable differences between groups of species in their contributions to forest flammability. Let us compare, for example, two quite different situations: first a deciduous broadleaf forest, and then grasses on the open range.

The foliage of broadleaf forests in full leaf shades the dead litter on the ground. The reduced solar radiation helps maintain temperature-humidity relationships favoring high moisture content of these dead materials. The forest canopy also reduces wind speeds near the ground—another favorable factor. The surface fuels are relatively unexposed to the elements until the forest is defoliated. Thus, ground fires in a deciduous forest in full leaf are rarely a serious threat. In addition, the live foliage of most deciduous American broadleaf forests is not very flammable, making crown fires in these types rare.

### *Grasses*

All living wildland vegetation responds to good and poor growing seasons as determined by the weather, but annual range grasses are much more sensitive to seasonal and short-term weather variations than are most other fuels. These grasses are shallow-rooted and thus depend primarily on adequate surface soil moisture for full top development. At best, annuals have a limited growth season. They mature, produce seed, and begin to cure or dry. But deficient surface moisture at the beginning of the season, or its depletion by hot, dry weather, may shorten the growth period. Similarly, because of the weather, the curing time may vary from 3 weeks to 2 months after noticeable yellowing.

Green grass is not flammable. After its moisture content has dropped to 30 or 40 percent during the curing stage, however, grass will burn on a good burning day. At the end of the curing period, annual grasses are dead fuels, fully exposed to the high temperatures of solar radiation and to the full force of the wind. Thus, annual grasses may reach a highly flammable stage while broadleaf foliage is still in prime growth.

Perennial grasses have deeper, stronger root systems than annuals and are somewhat less sensitive to short-term surface soil moisture and temperature changes. In regions that have marked growing seasons limited by hot, dry seasons or cold winters, the perennial grasses have, however, a growth and curing cycle similar to annuals, but dieback affects only leaves and stems down to the root crowns. The principal differences in moisture content result from a later maturing date and a slower rate and longer period of curing. In warm, humid areas, some stems and blades cure and die while others may remain alive, although more or less dormant. Often, such mixtures will burn in dry weather.

Any living vegetation can be consumed by fire of sufficient intensity burning in associated dead fuels. When vegetation is subjected to heating, however, marked differences appear among species in the rates of output of combustible volatiles. The result is that the living foliage of some species absorbs nearly as much heat to vaporize its contained water as it yields when burned. Living foliage of other species, except in the period of rapid spring growth, may add significantly to the total fire heat output. Among these latter species particularly, the current foliage moisture content is important in determining total flammability.

There is no convenient or practical method for obtaining inplace measurements of live-foliage moisture. A general estimate can be made by a close eye examination of the foliage, and by touching it. Light green succulent leaves of the current year's growth mark the period of maximum moisture content. Darkening and hardening of these leaves mark the beginning of steady moisture decline until dormancy sets in. Evergreen foliage is then mostly tough and leathery.

When a plant part dies, food manufacturing and growth stop and water circulation ceases. The contained water then evaporates until the dead tissues become "air-dry." The amount of water remaining is variable and always changing, depending on how wet or dry the environment happens to be.

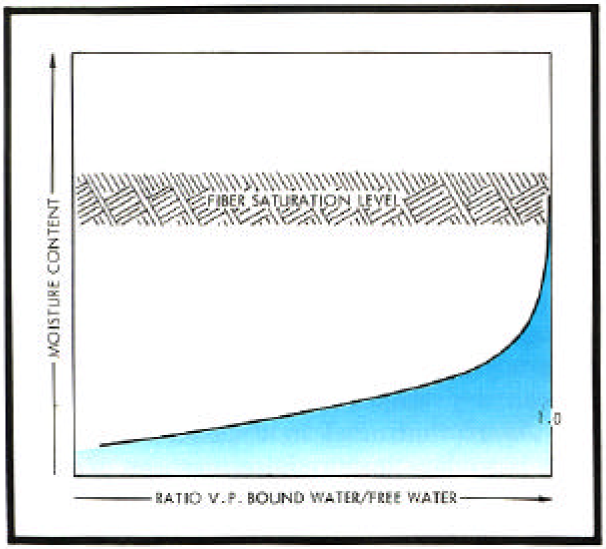
Dry, dead fuels adsorb moisture from the surrounding air when atmospheric humidity is high. When atmospheric humidity is low, moisture from moist fuels is evaporated into the surrounding air.

## Fuel-Wetting Processes

Dead vegetation retains its original structure of cells, intercellular spaces, and capillaries. It can soak up liquid water like a blotter, only more slowly, until all these spaces are filled. Dead vegetation may hold two or more times its own dry weight in water. Fine materials may absorb that much in a matter of minutes, while large logs may require a season or more of heavy precipitation. In some climatic regimes, the centers of large materials may never become completely saturated. One reason is that the rate of penetration slows down with increasing distance from the surface.

A second and equally important consideration in our understanding of fuel-wetting processes is the fact that the materials making up the dead cell walls are hygroscopic. Hygroscopic materials have an affinity for moisture which makes it possible for them to adsorb water vapor from the air. This process is one of chemical bonding. We will consider it in the light of our discussions of vapor pressure, evaporation, and condensation in chapter 3 and the related growth of ice crystals at the expense of water drops in chapter 9.

Molecules of water are attracted to, penetrate, and are held to the cell, or fiber, walls by the hygroscopic character of the cell material. The water molecules that penetrate and the few molecular layers that adhere to the cell walls are called bound water. The hygroscopic bond between the cell walls and the water molecules is strong enough to effectively reduce the vapor pressure of the bound water. The layer of water molecules immediately in contact with a cell wall has the strongest hygroscopic bond and lowest vapor pressure. Successive molecular layers have progressively weaker bonds until the cell walls become saturated. At that point, the vapor pressure in the outer layer of water on the cell wall is equal to that of free water, or saturation pressure. The amount of bound water at the fiber-saturation point varies with different materials. For most plant fuels it is in the range of 30 to 35 percent of the fuel dry weight.




**At moisture contents below the fiber-saturation level, the vapor pressure of bound water is less than that of free water. The ratio of these vapor pressures is unity at that level and decreases as moisture content decreases.**

The result of the bonding phenomenon is that free water cannot persist in a cell until the cell walls become saturated. Then free water can pass through the cell walls by osmosis. Below the saturation level, moisture is evaporated from cell walls of higher moisture content and taken up by cell walls of lower moisture content until the moisture in each cell attains the same vapor pressure. In this manner, much of the moisture transfer within fuels is in the vapor phase and always in the direction of equalizing the moisture throughout a particular piece of fuel.

Dead fuels will extract water vapor from the atmosphere whenever the vapor pressure of the outer surface of the bound water is lower than the surrounding vapor pressure. In a saturated atmosphere, this may continue up to the fiber-saturation point. Full fiber saturation rarely persists long enough in the absence of liquid water to permit the necessary internal vapor transfer.

## Fuel-Drying Processes

As noted above, fuel moisture can be raised to perhaps 300 percent by contact with liquid water, and to a maximum fiber saturation of around 30 percent in a saturated atmosphere through adsorption of water vapor. The reverse process of fuel drying is accomplished only by evaporation to the atmosphere.

The moisture content of dead fuels thoroughly wetted with free water within and on the surface decreases in three steps in a drying atmosphere, with different drying mechanisms dominant in each. The first step is called the constant-rate period. The rate here is independent of both the actual moisture content and the hygroscopic nature of the fuel. It ends at the critical moisture content, the condition in which the total fuel surface is no longer at or above fiber saturation. The second is an intermediate step, which we will call the decreasing-rate period. During this period, there is a decreasing saturated fuel surface area and an increasing proportion of moisture loss through the slower removal of bound water. The period ends when all the fuel surface reaches the fiber-saturation level. The third step is the falling-rate period when the hygroscopic nature of dead fuel becomes dominant in the drying process.

The process of moisture loss in the constant-rate period is somewhat simpler than those of the succeeding steps. Drying takes place by evaporation exactly as from any free-water surface. It will proceed whenever the surrounding vapor pressure is less than saturation pressure, and at a rate generally proportional to the outward vapor-pressure gradient. Wind speed during this period does not affect ultimate attainment of the critical moisture content level. But it does affect the time required to reach that point. When there is evaporation from a water surface in calm air, a thin layer next to the interface between the free water and air tends to become saturated with water vapor. This saturation near the water surface decreases the evaporation rate and dissipates only by relatively slow molecular diffusion in the air. Wind breaks up this thin layer and blows it away, thereby speeding up the evaporation process.

The intermediate decreasing-rate period may best be described as a transition step in which there is a variable change in moisture loss rate. This rate begins changing slowly within the defined limits from the linear rate of the constant-rate period to the orderly decreasing rate characteristic of the falling-rate period. Variations in the rate of drying during the decreasing-rate period are caused by fuel and environmental factors that are difficult to evaluate and for which no general rules are available. This period is often considered as part of what we have called the falling-rate period when the error involved in calculations is considered tolerable. It is separated for our purposes because it applies only to drying and is not reversible in the sense of vapor exchange between fuel and air as is the case in the falling-rate period. Wind speed still plays a significant role in the drying process during this period.

The falling-rate period of drying depends upon an outward gradient between the bound-water vapor pressure and the ambient vapor pressure in the atmosphere. As moisture removal progresses below the fiber-saturation point, the bound-water vapor pressure gradually declines, and the vapor-pressure gradient is gradually reduced. Either of two conditions must prevail to assure continued significant drying: One is to maintain a surrounding vapor pressure appreciably below the declining bound-water vapor pressure; the other is addition of heat to the fuel at a rate that will increase its temperature and correspondingly its bound-water vapor pressure. Both processes operate in nature, sometimes augmenting and sometimes opposing each other.

As drying progresses toward lower moisture-content values, a vapor pressure gradient is established within the fuel. The external vapor pressure needed to maintain this gradient must therefore be quite low. Under these conditions, molecular diffusion into the atmosphere is more rapid than that within the fuel. This results in a lesser and lesser tendency for thin layers of higher vapor pressure to form at the fuel surface. For this reason, the effect of wind speed on drying gradually decreases at moisture levels progressively below fiber saturation. The effect may never be eliminated, but at low moisture levels it has little practical significance.

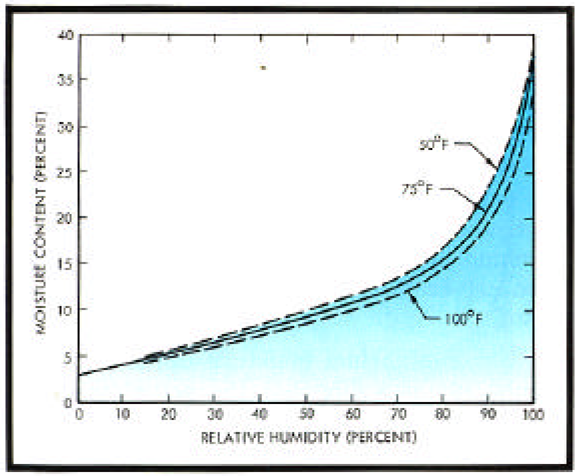
## Concept of Moisture Equilibrium

Moisture equilibrium has meaningful application to forest-fuel moisture only in the range of moisture-content values between about 2 percent and fiber saturation. This is the range covered by the falling-rate period of drying. Fuel will either gain or lose moisture within this range according to the relative states of the fuel and its environment. The amount, rate, and direction of moisture exchange depend on the gradient between the vapor pressure of the bound water and the vapor pressure in the surrounding air. If there is no gradient, there is no net exchange, and a state of equilibrium exists.

The equilibrium moisture content may be defined as the value that the actual moisture content approaches if the fuel is exposed to constant atmospheric conditions of temperature and humidity for an infinite length of time. The atmospheric vapor pressure is dependent upon the temperature and moisture content of the air. The vapor pressure of the bound water in fuel depends upon the fuel temperature and moisture content.

Assuming that the fuel and the atmosphere are at the same temperature, then for any combination of temperature and humidity there is an equilibrium fuel-moisture content. At this value, the atmospheric vapor pressure and the vapor pressure of the bound water are in equilibrium. This point almost, but not quite, exists in nature. Small vapor-pressure differences can and do exist without further moisture exchange. This is demonstrated by the fact that a dry fuel in a more moist environment reaches equilibrium at a lower value than a moist fuel approaching the same equilibrium point from above. For this reason also, reduction of humidity to zero does not reduce fuel moisture to that value. Vapor exchange involving bound water is not as readily attained as is free water and atmospheric vapor exchange. At low vapor-pressure gradients involving bound water, there is not sufficient energy at normal temperatures and pressures to eliminate these small gradients.

Equilibrium moisture content has been determined in the laboratory for numerous hygroscopic materials, including a variety of forest fuels. The usual procedure is to place the material in an environment of constant temperature and humidity, leaving it there until the moisture content approaches a constant value. The process is then repeated over the common




**The equilibrium moisture content—the average for six fuel types is shown—depends mainly upon the relative humidity, and to a lesser extent on temperature.**

ranges of humidity and temperature encountered in nature. Continuous or periodic weighing shows the changing rates at which equilibrium is approached from both directions. Different fuel types usually have different equilibrium moisture contents, but for most fire-weather purposes it is satisfactory to use the average determined for a number of fuels.

The rates at which moisture content approaches the equilibrium value vary not only with the kind of fuel material, but with other characteristics such as fuel size and shape, and the compactness or degree of aeration of a mass of fuel particles. For any one fuel particle with a moisture content below fiber saturation, the rate of wetting or drying by vapor exchange is theoretically proportional to the difference between the actual moisture content and the equilibrium moisture content for the current environmental conditions.

This means, for example, that when actual fuel moisture is 10 percent from its equilibrium value, the rate of increase or decrease is 10 times as rapid as if the moisture were within 1 percent equilibrium. This relationship indicates that moisture content approaching equilibrium follows an inverse logarithmic path.

Use of the equilibrium moisture-content concept makes it possible to estimate whether fuel moisture is increasing or decreasing under a particular environmental situation, and the relative moisture stress in the direction of equilibrium. This by itself, however, is a poor indicator of the quantitative rate of moisture-content change. To it, we must also add the effect of size or thickness of the fuel in question.

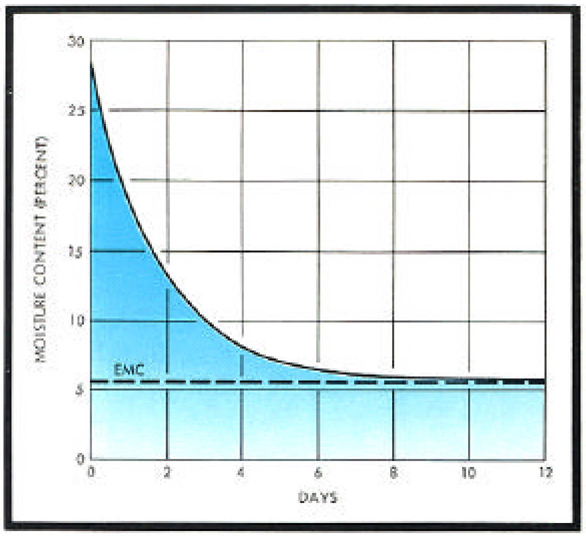
### *Timelag Principle*

One method of expressing adsorption and drying rates based on both equilibrium moisture content and fuel characteristics makes use of the timelag principle, common to a variety of natural phenomena. According to this principle, the approach to equilibrium values from moisture contents either above or below equilibrium follows a logarithmic rather than a straight-line path as long as liquid water is not present on the surface of the fuels.

If a fuel is exposed in an atmosphere of constant temperature and humidity, the time required for it to reach equilibrium may be divided into periods in which the moisture change will be the fraction (1—1/e)~ 0.63 of the departure from equilibrium. The symbol, e, is the base of natural logarithms, 2.7183. Under standard conditions, defined as constant 80°F. temperature and 20 percent relative humidity, the duration of these time periods is a property of the fuel and is referred to as the timelag period. Although the successive time-lag periods for a particular fuel are not exactly equal, the timelag principle is a useful method of expressing fuel-moisture responses if average timelag periods are used.

To illustrate the moisture response, let us assume that a fuel with a moisture content of 28 percent is exposed in an environment in which the equilibrium moisture content is 5.5 percent. The difference is 22.5 percent. At the end of the first timelag period, this difference would be reduced 0.63 x 22.5, or about 14.2 percent. The moisture content of this fuel would then be 28 —14.2, or 13.8 percent. Similarly, at the end of the second timelag period the moisture content would be reduced to about 8.6 percent, and so on. The moisture content at the end of five or six timelag periods very closely approximates the equilibrium moisture content.

The average timelag period varies with the size and other factors of fuels. For extremely fine fuels the average period may be a matter of




**Drying curve of 2-inch layer of litter in an environment for which the equilibrium moisture content is 5.5 percent.**

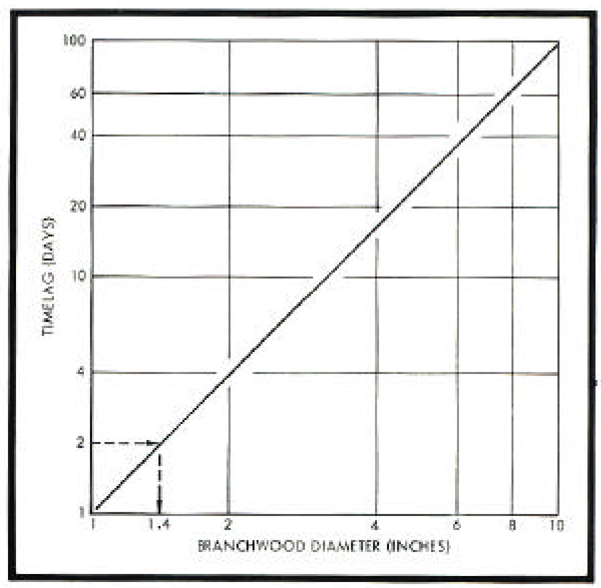
minutes, while for logs it ranges upward to many days. Using the timelag principle, we can describe various fuels—irrespective of type, weight, size, shape, compactness, or other physical features—as having an average timelag period of 1 hour, 2 days, 30 days, and so on. Dead branchwood 2 inches in diameter, for example, has an average timelag period of about 4 days. Logs 6 inches in diameter have an average timelag period of about 36 days. A 2-inch litter bed with an average timelag period of 2 days can be considered the equivalent, in moisture response characteristics, of dead branchwood (about 1.4 inches in diameter) having a similar timelag period if there is no significant moisture exchange between the litter and the soil.

Thus far we have been discussing the moisture behavior of homogenous fuel components exposed to uniform atmospheric conditions. These conditions are never uniform for long. Except for very fine material, it is rare that even one component is really near equilibrium. Most wildland dead fuels consist of such a variety of components that it is impossible for the whole fuel complex to be at equilibrium moisture content at any one time. Nevertheless, a working knowledge of equilibrium moisture-content processes and fuel timelag differences permits one to make useful estimates of current fuel-moisture trends.

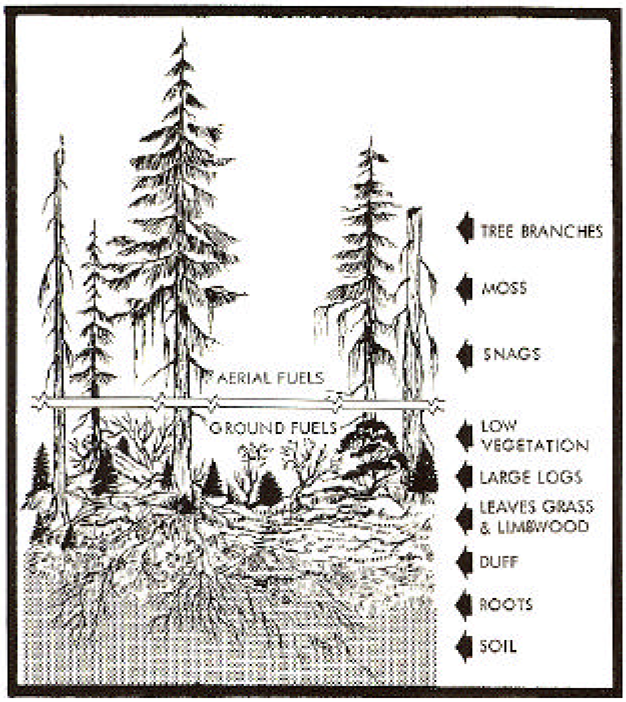
### Aerial and Ground Fuels

Two types of dead fuel are of particular interest. Dead foliage, twigs, and branches still attached to living vegetation or otherwise suspended above ground respond to precipitation and subsequent atmospheric conditions mainly as individual components according to their respective kinds and sizes. Detached components, forming more-or-less prone fuel beds on the forest floor, often undergo much more complex fuel-moisture changes.

Types of forest floor coverings vary widely depending on the nature of the forest and climatic region. In areas of rapid decomposition, the surface may be covered with only 1 or 2 year's accumulation of dead foliage and a few twigs. At the other extreme, there may be many years of accumulated foliage, branches, and logs consisting of all degrees of preservation and decay from the top downward to, and mixed with, the mineral soil. There is tremendous variety between these extremes. The common feature of all, however, is that only the upper surface is exposed to the free air while the lower surface is in contact with the soil.




**The average timelag period of branchwood and logs varies with the fuel diameter. Other fuels may be compared with these. A 2-inch litter bed with an average timelag period of 2 days, for example, may be considered the equivalent of 1.4-inch dead branchwood having the same average timelag period.**

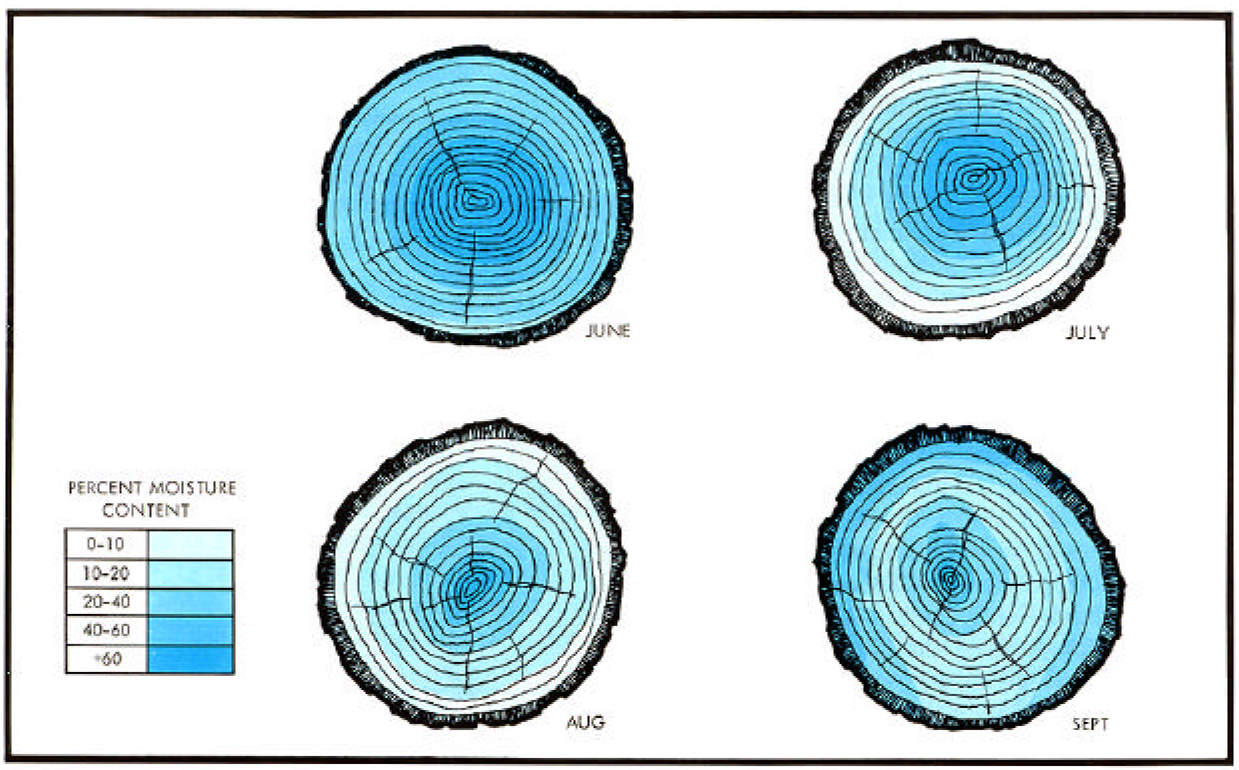



**Aerial fuels respond to precipitation and atmospheric conditions as individual components, according to their respective kinds and sizes. Fuels on the ground tend to become compacted and have more complex moisture changes.**

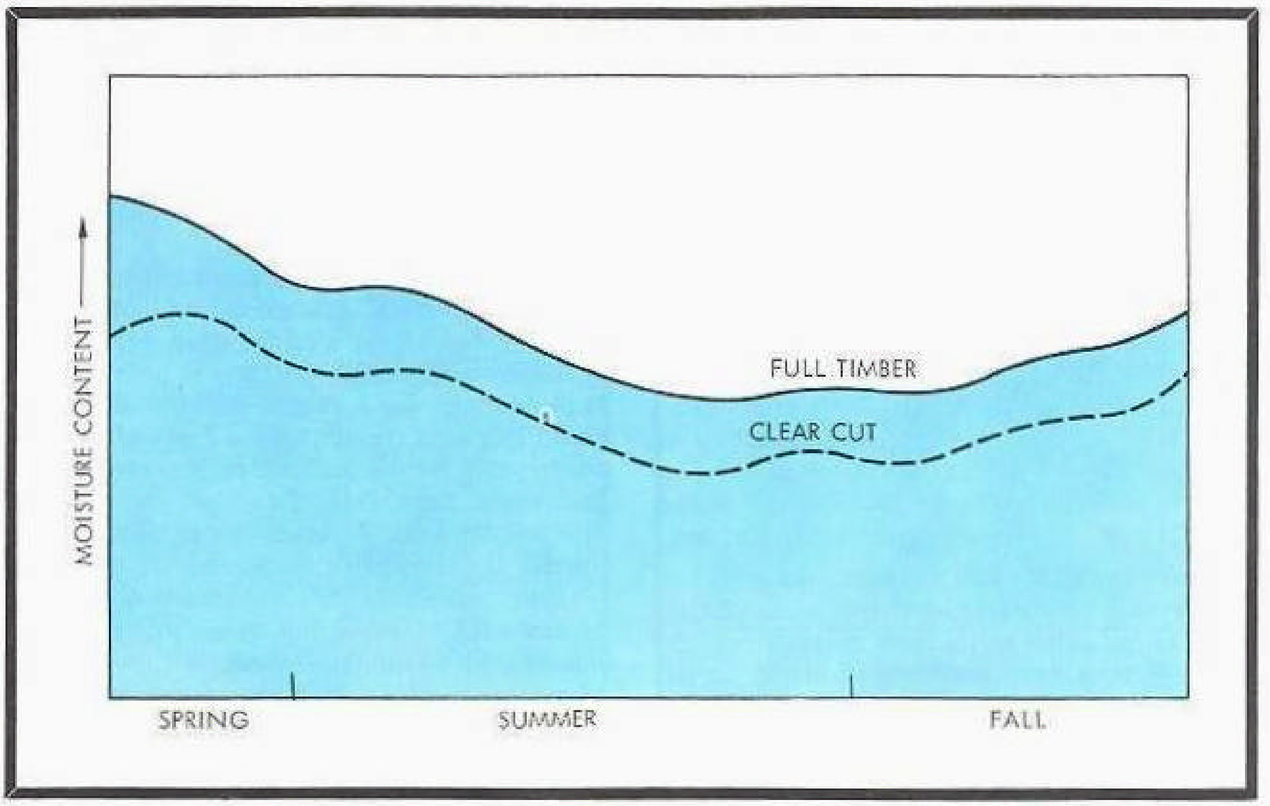
There is one moisture gradient between the fuel and the air, another between the fuel and the soil, and still another between the top and bottom of the fuel bed itself. In deep and compact fuel beds, air circulation in the lower layers may be nearly nonexistent. Precipitation soaking down through the fuel into the soil may then produce relative humidities near 100 percent at the lower levels, and this can persist for appreciable times. Subsequent drying starts at the top and works downward. In deep fuels, it is not uncommon for the surface layer to become quite flammable while lower layers are still soaking wet. Here, the moisture gradient is upward.

Reverse gradients also occur after prolonged drying, resulting in the topsoil and lower duff becoming powder dry. Then morning dew on the surface, high relative humidity, or a light shower may cause a downward moisture gradient.

These changes in upward and downward moisture gradients are common in most compacted fuel beds. In some situations, they may even be part of the diurnal cycle of moisture




**A large log, wet from winter precipitation, dries through the summer from the outside in. In the fall, as rains begin and temperatures and humidities moderate, the process is reversed and the log begins to take on moisture from the outside in.**




**Logs under a forest canopy remain more moist through the season than those exposed to the sun and wind. These curves are 13 – year averages for large logs of 6-, 12-, and 18-inch diameters.**

Change in response to diurnal changes in temperature and relative humidity. This is particularly true in open forest stands where much of the surface littler is exposed to direct radiant cooling to the sky at night.

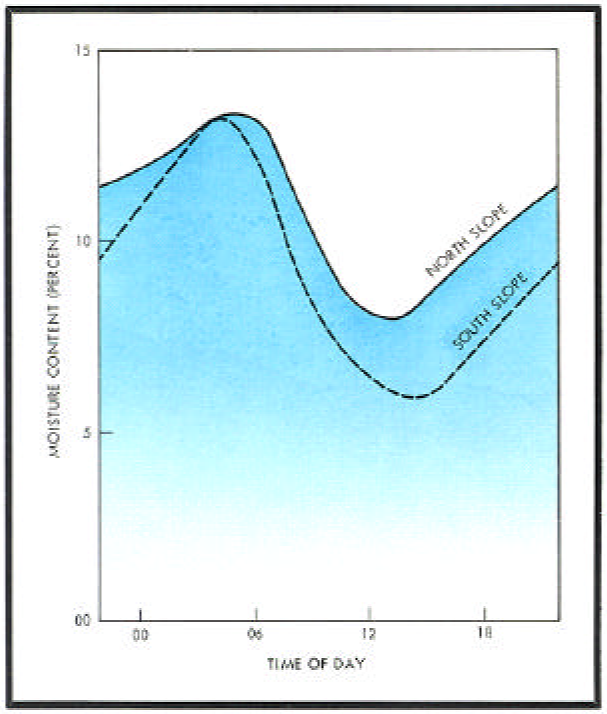
The amount of fuel available for combustion is often determined by these interior moisture gradients. In some cases, for example, fire may only skim lightly over the surface; in others, the entire dead-fuel volume may contribute to the total heat output of the fire.

***Effects of Canopy, Clouds, Exposure, Elevation, Wind***

During clear weather, fuel-bed surfaces exposed to full midday sum may reach temperatures as high as 160°F. or more. Not only does this greatly increase the bound-water vapor pressure, but it also warms the air near the surface and reduces relative humidity. The combination often results in surface fuel moistures 4 to 8 percent below those in adjacent shaded areas. Similarly at night, cooling of these exposed fuel surfaces may cause dew to form on them, while it does not form under the tree canopy. Surface fuel moistures and accompanying changes in moisture gradients are thus commonly much greater, and at the same time much more spotty, in open forest stands than under forests having closed-crown canopies. Clouds also tend to reduce the diurnal extremes in fuel moisture.

North-facing slopes do not receive as intense surface heating as level ground and south exposures, so they do not reach the same minimum daytime moistures. The highest temperatures and lowest fuel moistures are usually found on southwest slopes in the afternoon. In mountain topography, night temperatures above the nighttime inversion level ordinarily do not cool to the dew point; therefore, surface fuel moistures do not become as high as those at lower elevations.

Earlier in this section, we emphasized the effect of wind on fuel drying by preventing a




**Fuel moistures are affected by aspect. Except for the early morning hours, fuel moistures will be lower throughout the day on south slopes than on north slopes. Southwest slopes usually have the lowest afternoon fuel moistures.**

rise in vapor pressure adjacent to the fuel. But moderate or strong winds may affect surface temperatures of fuels in the open and thereby influence surface fuel moisture. During daytime heating, wind may replace the warm air layers immediately adjacent to fuel surfaces with cooler air. This in turn raises the relative humidity in that area and lowers the fuel-surface temperature. Fuel drying is thereby reduced. At night, turbulent mixing may prevent surface air temperatures from reaching the dew point, thus restricting the increase of surface fuel moisture.

Foehn winds are frequently referred to as drying winds because they are so often accompanied by rapid drying of forest fuels. In the case of the foehn, it is warm and extremely dry air that is responsible for desiccation. The important role of the wind here is to keep that warm, dry air flowing at a rapid rate so that it does not become moist by contact with the surface either by day or night. The reverse is true, of course, when moist winds blow over dry fuels. They bring in a continuous supply of moisture to maintain a pressure gradient favorable for fuel-moisture increase. In all of these moisture-exchange processes, it should be remembered that wind has quite varied and complex effects on fuel-moisture regimes.

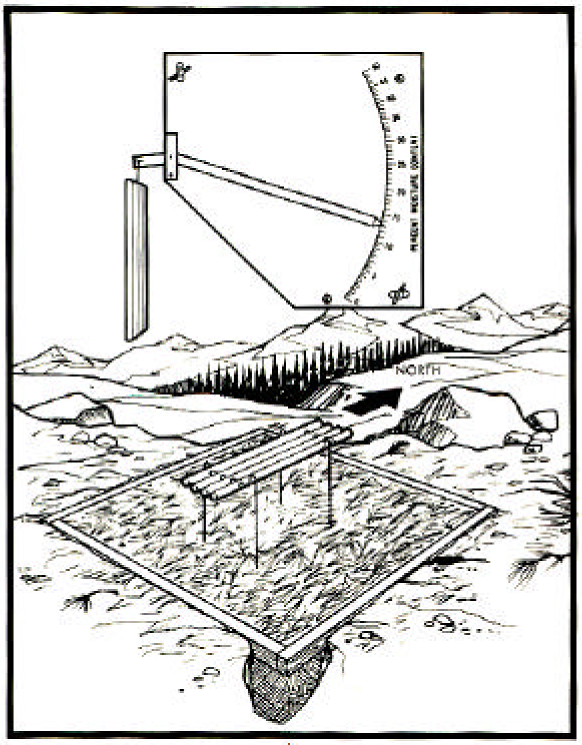
### *Slash*

Slash from thinning or harvest cutting of coniferous forests is a special and often particularly hazardous kind of dead fuel. Often, it is flammable from the time it is cut, but it is particularly hazardous if added to significant quantities of flammable dead fuels already on the ground. As the slash dries, it becomes more and more flammable. The slash of different species dries at different rates, and within species the drying rates depend on degree of shading, season of cutting, weather, and size of material. Needles and twigs dry faster on lopped than on unlopped slash. Within a matter of weeks, however, it is not necessary to consider slash needle and twig moisture different from that of older dead fuels. Stems, of course, require longer periods of seasoning to approach the fuel moisture of their older counterparts.

## Estimating Dead Fuel Moisture

The moisture content of dead fuels cannot be measured conveniently in the field. For fire-control purposes, it is usually estimated indirectly by various methods. Very fine, dead fuels such as cured fine grass, certain lichens and mosses, well-aerated needles and hardwood leaves, and the surface layer of larger fuels may be in approximate equilibrium with their immediate environments. Except after rain, a reasonably accurate estimate of their moisture content, and therefore their flammability, may be obtained from the equilibrium moisture content corresponding to the immediately surrounding air temperature and humidity. But, even here, it helps to know whether the moisture content is rising or falling.

A method used in some regions to estimate the moisture content of medium-sized fuels is to determine the moisture content of fuel-moisture indicator sticks. A set of sticks consists of four 1/2-inch ponderosa pine sapwood dowels spaced 1/4 inch apart on two 3/16-inch dowels. The 1/2 –inch dowels are approximately 20 inches long. Each set is carefully adjusted

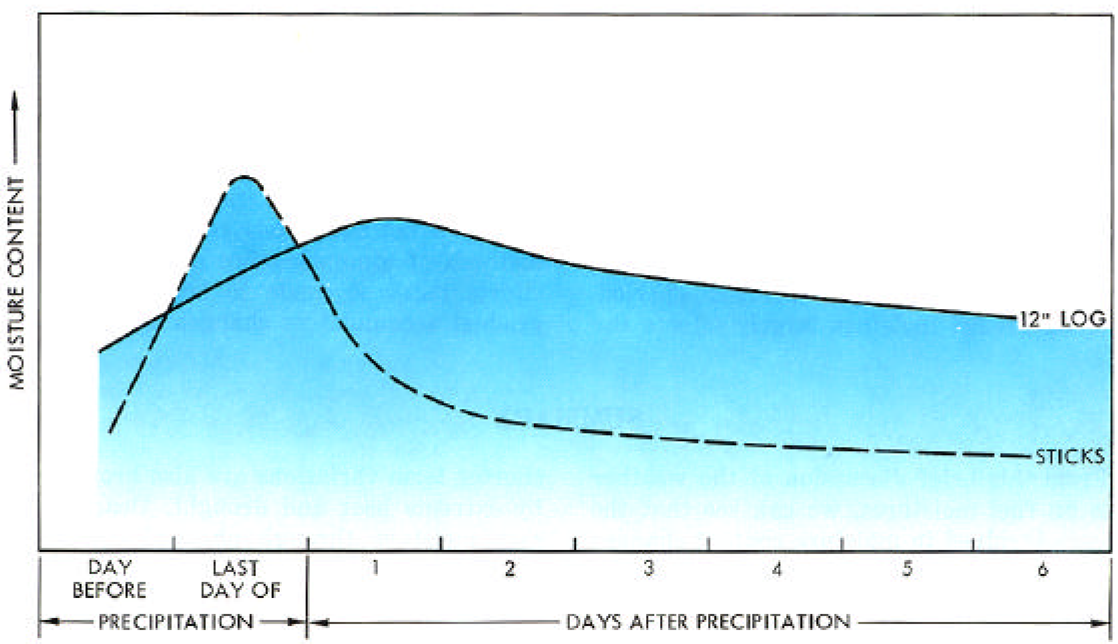



**Fuel-moisture indicator sticks of the ‘1/2-inch size are used to estimate th. moisture content of dead fuels of comparable size. They are exposed on a wire rock 10 inches above a bed of litter. By weighing them, their moisture content can be obtained.**

to weigh 100 grams when ovendry. The sticks are exposed 10 inches above a litter bed in the open on wire brackets. They are weighed at least once every day, and their moisture contents are computed from their known dry weights. Scales calibrated to read directly in percent moisture content are available.

The indicated moisture represents the cumulative effects of past changing weather factors on these standardized fuel simulators over a period of time preceding the observation. These indicated values may be modified by current weather or other factors when necessary to more closely approximate actual field conditions. Other systems and devices may also be used as weather integrators in lieu of moisture indicator stick weights.

The moisture content of larger fuels is usually estimated from systematic observations of precipitation and some indicator of daily drying conditions, such as maximum temperatures and day length, or the moisture-content trends of indicator sticks referred to above. From empirical relationships involving amounts of precipitation, number of days without precipitation, and daily drying conditions, the moisture content of large fuels can be estimated.




**Measurements of the moisture contents of different sizes of fuels before, during, and after precipitation show that larger fuels, such as logs, are slow to react to both wetting and drying.**

## MIXTURES OF LIVING AND DEAD FUELS

We have noted that somewhat different processes govern the changes in moisture contents of living plant foliage and those of dead forest fuels. It is also significant that the upper flammability limit of most dead fuels under ordinary field conditions is about 25-30 percent moisture content. The living foliage of many evergreen trees and shrubs may burn well with moisture contents of over 100 percent, probably because of volatile oils released, but usually some intermixed dead fuels are necessary to maintain combustion. The different moisture contents in intermixed living and dead fuels do not always rise and fall in the same pattern. They must be evaluated separately to determine the flammability of the complex as a whole at any given time.

The manner in which living and dead fuel mixtures may augment or oppose each other depends somewhat on the nature of the local fire weather in relation to the growing season. A brief dry spell during a period of new leaf development and growth may cause intermixed dead fuels to become reasonably dry. They do not burn briskly, however, because much of the heat needed for fire propagation is absorbed by the succulent foliage. If such a dry spell occurs after the foliage reaches maturity, or when the foliage is dormant, flammability of the complex may become high to extreme.

Areas with a distinct summer dry season tend to have a more or less regular seasonal pattern of foliage and dead-fuel moisture variation. In such areas, it is common for foliage moisture to start increasing about the time dead fuels begin to dry, reaching a maximum in late spring or early summer. During this period, increasing foliage moisture largely offsets the effects of continued drying of the associated dead fuels. By mid or late summer, however, the foliage has reached the flammability point. Beyond this time, continued foliage moisture decreases, coupled with seasonal cumulative drying of larger dead fuels and deep litter beds, produce increasing flammability until fall rains begin.

Differences among species, total and relative amounts of living and dead fuels, their interrelationships in space, as well as vagaries in weather and growing seasons, occur in infinite variety. Hence, evaluation of the current flammability of most live-dead fuel complexes requires local appraisal and interpretation based on experienced judgment.

One of the most difficult situations to evaluate is that brought about by drought resulting from consecutive years of deficient precipitation. Such periods of persistent drought occur in all forest regions at irregular intervals, often many years apart. Both living and dead fuels are adversely affected. Both old and new living foliage will be abnormally deficient in moisture. The ratio of attached dead twigs and branches will increase markedly. Large logs may become dry enough to burn to a white ash residue. Stumps and their roots may become dry enough to burn deep into the ground. Thus, the flammability of both living and dead fuels will increase, and at the same time the ratio of dead to live fuel increases. The gradual trend in rising fire danger is subtle, but it has a pronounced accumulative effect. This slow trend usually is not adequately recognized by routine methods of computing fire danger, and special efforts must be made to keep aware of the gradual accumulative changes in flammability.

## SUMMARY

From this brief discussion of the weather effects on fuel moistures, we can see that the processes involved in moisture content changes are very complex. Living plants and dead fuels respond quite differently to weather changes. The moisture content of a living plant is closely related to its physiology. The major variations in moisture are seasonal in nature, although shorter term variations are also brought about by extreme heat and drought. Dead fuels absorb moisture through physical contact with liquid water such as rain and dew and adsorb water vapor from the atmosphere. The drying of dead fuels is accomplished by evaporation.

Under suitable drying conditions, first the free water in the cellular spaces evaporates;

then the bound water held to the cell walls evaporates and is absorbed by the atmosphere. The nature of the drying and wetting processes of dead fuels is such that the moisture content of these fuels is strongly affected by weather changes. These moisture contents are influenced by precipitation, air moisture, air and surface temperatures, wind, and cloudiness, as well as by fuel factors such as surface to volume ratio, compactness, and arrangement.

We have now completed our discussion of the individual fire-weather elements and their effect on the moisture content of forest fuels. In the final chapter, we will learn how fire weather varies from one region to another over the North American Continent.