3

Wildland Fuels

Fuel is a critical leg in both of the fire triangles: fuel, oxygen, and heat of the fire fundamentals triangle (Figure 1.2) and fuel, topography, and weather of the fire environment triangle (Figure 2.2). Fuel doesn't cause fire, but it certainly changes the character of a fire, affecting the ease of ignition as well as fire size and intensity. Understanding fuel is important to all aspects of wildland fire, including fire suppression, fuel management, smoke management, wildland/urban interface, forest health and ecosystem management, and global climate change.

An examination of fuel depends on the scale under consideration: fire fundamentals, fire behavior, landscape, or global scale (Figure 1.1). When looking at fire on the fire fundamentals scale in Chapter 1, we examined the intrinsic fuel properties and their role in the combustion process. Intrinsic properties are the chemical and physical properties that define the fuel elements. As we move to the fire behavior scale, we look at the whole fuel complex—ground, surface, and crown fuels—and descriptors such as arrangement, size, and live-to-dead ratio. At the landscape level, we consider relationships among fuel complexes on the terrain and their size and location. This includes the wildland/urban interface, for example. The view of fuel for

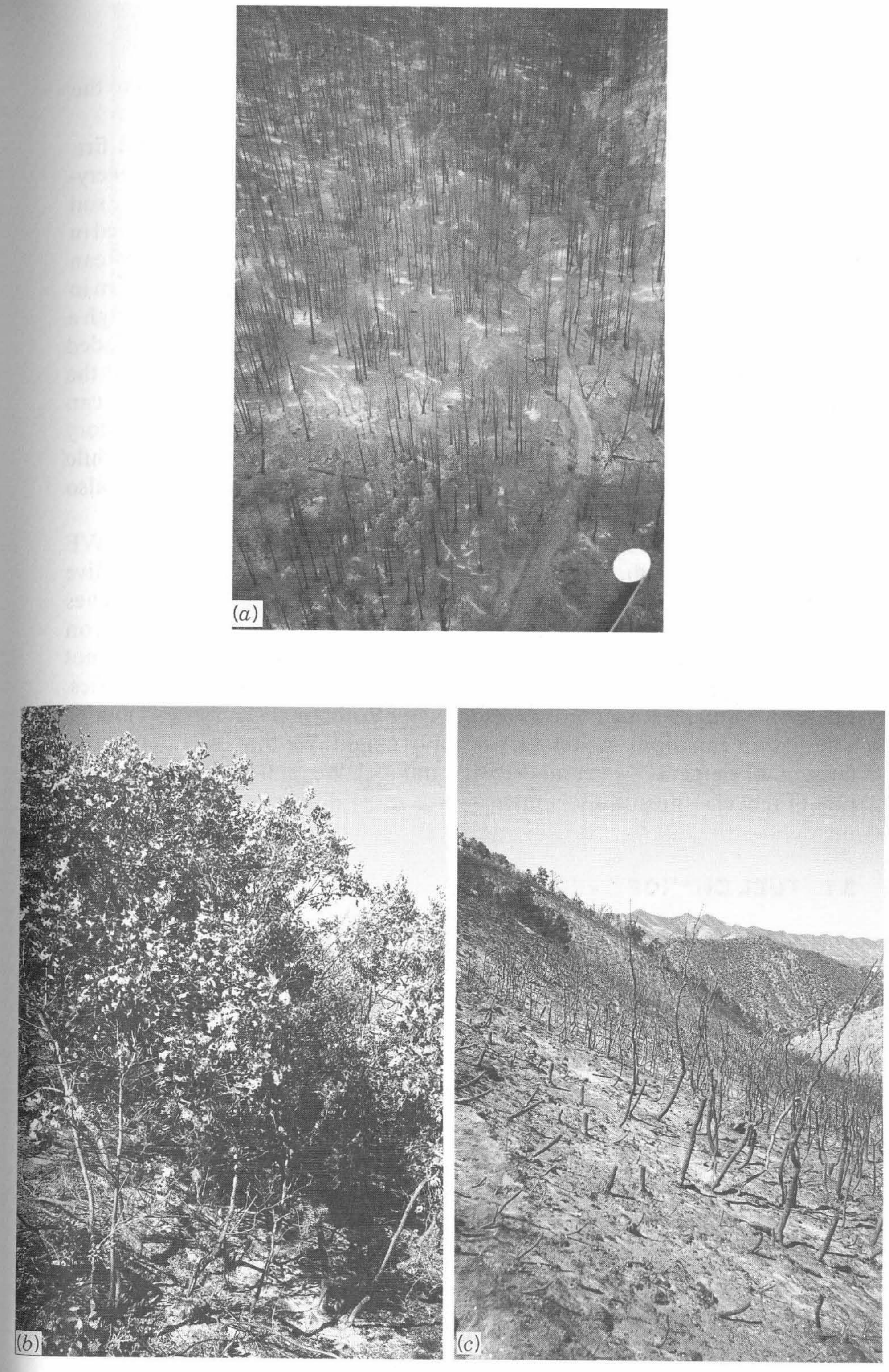


Figure 3.1. *Total fuel load is all of the vegetative material above mineral soil. Available fuel is a portion of that value depending on environmental conditions. (a) Under very dry conditions nearly all of the surface fuel is consumed. A line of ashes is all that remains of logs after the Dude fire in Arizona (26 June 1990).* Photo by Patricia L. Andrews, USDA Forest Service. *(b) An underburn through the litter dried the Gambles oak on the South Canyon fire.* From USDA/USDI (1994). *(c) Gambles oak remaining at the fatality site of the South Canyon fire, Colorado, 1994.* From USDA/USDI (1994).

this chapter is mostly at the fire behavior scale, with some references to the landscape level.

Wildland fuel is the vegetative material that burns in a wildland fire. Several more specific definitions must be considered. *Biomass* includes everything—all vegetative and animal material including the roots deep in the soil (although the term is sometimes used to describe the portion that is involved in wildland fire). *Phytobiomass* is the plant material above mineral soil, and can be considered *total fuel*. *Potential fuel* is the material on a site that might burn in a most intense fire, a value that is generally less than the total fuel. Although a fire doesn't consume the entire bole of living trees, that component is included as part of the total fuel; it is not included as potential fuel. *Available fuel* is the fuel that is available for combustion in a given fire (Figure 3.1). The value can vary widely for a site, depending on environmental conditions. An understory burn might consume only part of the grass, litter, and shrubs on one day, while on another day with more favorable burning conditions the fire might also involve the overstory and the duff.

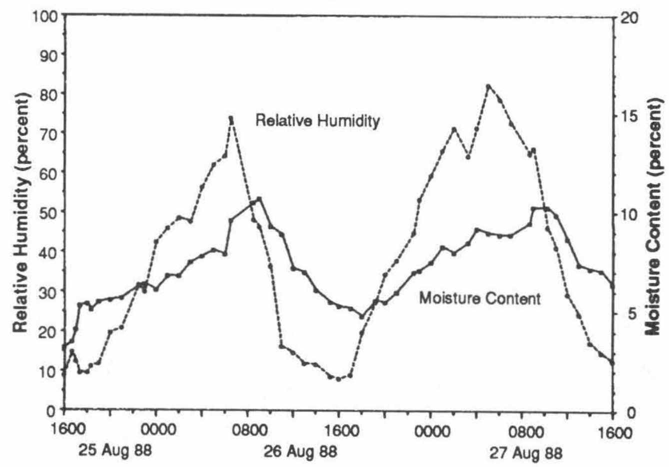
The meaning of the term "fuel" varies with the application. The BEHAVE fire behavior prediction system, for example, refers to fuel as surface fuel, live components less than $\frac{1}{4}$ inch in diameter and dead components up to 3 inches in diameter (not ground or crown fuel; not logs). Logging slash inventories, on the other hand, are concerned with dead woody surface fuel (not live fuel; not herbaceous plants, shrubs, or leaf litter). Quantification of fuel also varies. Fuel depth and packing ratio are required for Rothermel's fire spread model, whereas an emissions model requires only weight. We first discuss descriptions of all elements that compose wildland fuel. We then give several examples of fuel classification schemes.

3.1 FUEL CHANGE OVER TIME

Fuel can be described in terms of fuel type and fuel state. *Fuel type* is a description of the fuel itself, while *fuel state* is dependent on changing environmental conditions. Fuel state is related to moisture content.

Fuel, like everything in nature, is not static. It changes over time—from hourly change in the moisture content of dead twigs to successional changes that occur over decades. A discussion of the way that fuel changes over time provides a framework for discussion of both fuel type and fuel state. Fuel

(*a*)



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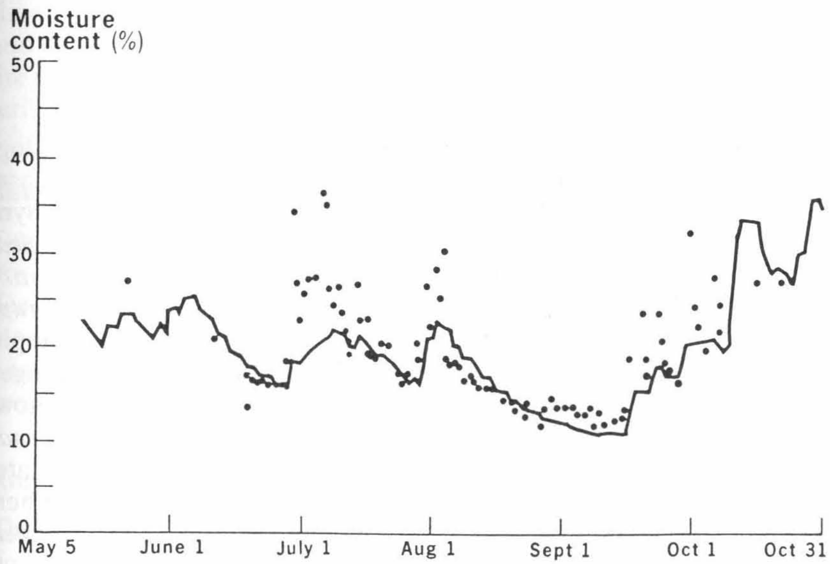
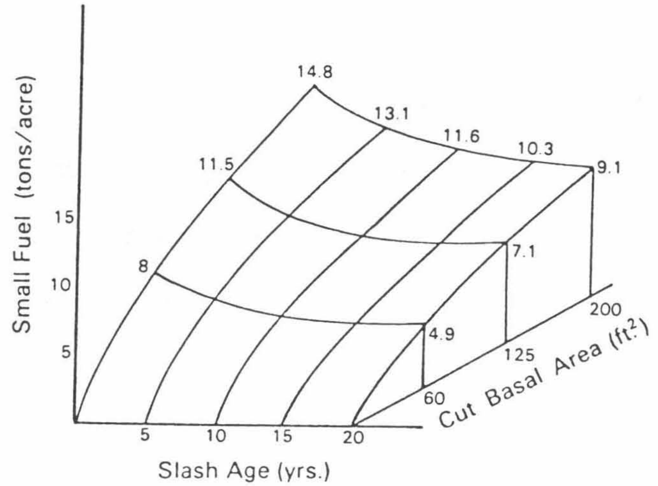


(*c*)

Figure 3.2. *Fuel changes occur at various time scales: abrupt, diurnal, seasonal, annual, and successional. (a)* Abrupt *changes in fuel arrangement caused by Hurricane Hugo, North Carolina, 1989.* Photo by Ron Coats, USDA Forest Service. *(b)* Diurnal *variations of fine dead fuel moisture and relative humidity during the fires in Yellowstone National Park, 1988.* From Hartford and Rothermel (1991). *(c)* Seasonal *variation in the moisture of large logs at Priest River Experimental Forest.* From Fosberg and others (1981). *(d)* Annual *change of small fuel loadings versus thinning slash age and basal area cut as a function of slash age.* From Carlton and Pickford (1982). *(e)* Successional *change after fire.* Carol Evans, USDA Forest Service.



(*d*)

(*e*)

Figure 3.2. (Continued)

change can be caused by (1) *disturbance*, both human and natural, such as logging, construction of roads and structures, hurricanes, fire, insect, and disease; (2) *weather*, including diurnal changes in air temperature and humidity, synoptic weather changes, and seasonal change; and (3) *biological/physiological cycles*, such as greenup and curing, leaf drop, decay, and plant succession.

We consider fuel change over five time scales (Figure 3.2): (1) *Abrupt* changes due to a disturbance result in changes in fuel type. Frost is an example of an abrupt change that results in a change in fuel state. (2) *Diurnal* changes occur on an hourly timeframe. As temperature and humidity vary throughout the 24-h cycle, so does fine dead fuel moisture (state change). (3) *Seasonal* changes occur on a monthly scale and can be changes in both type and state. (4) *Annual* changes in fuel are changes in fuel type from one year to another. (5) *Successional* changes occur over very long time periods, decades or even hundreds of years.

Abrupt Change

Fuel type can change abruptly due to human or natural causes. Human management actions such as logging or chaining cause a change in the amount and arrangement of the fuel. Similarly, natural forces such as fire or wind cause abrupt change in fuel type (Figure 3.2a).

Fuel state can change abruptly as a result of frost. The foliage may look the same, remaining green immediately after a frost, but there can be a dramatic moisture change, greatly affecting fire behavior. A similar dangerous situation results from an abrupt change in moisture when a fire has burned through an area, drying fuels that are not involved in the fire. The fire burns through the grass and litter, drying the brush (see Figure 3.1c) or through the surface fuels drying the overstory. A change in wind direction can result in a reburn of the area, this time through another fuel layer. This is a dramatic example of the concept of "available fuel." Part of the fuel was available the first time, but because of a change in wind and in the moisture of the dried fuel, more of the fuel complex becomes available, sometimes with disastrous results.

Diurnal Change

The moisture content of fine dead fuel changes throughout the day in response to weather changes, such as temperature, relative humidity, and solar radiation. Figure 3.2b shows the diurnal cycle of fine dead fuel moisture and relative humidity for two days during the fires in Yellowstone National Park in 1988. The fuel moisture remained low at night, allowing the fires to burn vigorously.

Because fine dead fuels have such an influence on fire spread, hourly changes in that fuel component are important. It is possible to estimate the times of day when fire will be most active—generally increasing midafternoon and decreasing at night. If fine dead moisture remains low (dry) at night the fire may continue active burning. This information is also used in timing prescribed fire ignition.

Seasonal Change

Fuels change throughout the year due to cumulative effects of weather and to normal biophysiological cycles. The greenup and curing of live vegetation, deciduous leaf drop, and changes in moisture of logs and duff occur on a monthly scale. Some seasonal changes are in fuel type, others in fuel state. Leaf drop changes the fuel type; changes in moisture of logs and duff and greenup and curing are changes in state (Figure 3.2c).

Annual Change

The fuel complex changes from year to year due to vegetation growth and decay as well as buildup and decay of dead vegetation. Yearly changes in the southeastern United States in the palmetto–galberry type are discussed in a selected example at the end of the chapter. Changes in ponderosa pine fuel beds after thinning from one drainage on the eastern side of the Cascade Range in Washington State have been described mathematically by Carlton and Pickford (1982) as a function of slash age (time since logging) and basal area of trees removed (Figure 3.2d). The functional relationship can be used to estimate fuel change over time as an assessment of potential fire hazard after logging.

Successional Change

Fuel also changes on a much longer time frame, by tens and hundreds of years. Vegetation changes type over long periods of time through successional changes, from grass to brush to timber. Patterns are changed as a result of human intervention, such as fire suppression (Figure 3.2e).

3.2 FUEL DESCRIPTION

To describe fuel type, we start by examining those physical *properties* that affect the way the material burns. Properties include quantity, size, compactness, and arrangement. We then look at fuel *components*, which are related to the way that vegetation grows. Components may be specified as ground, surface, and crown fuel as well as grass, litter, brush, or overstory. We then move to fuel *complexes*, which are associations of components. Examples are sagebrush/grass and timber with grass and litter understory.

Properties

Intrinsic fuel properties (heat content, chemical content, etc.) were discussed in Chapter 1. Here we discuss extrinsic properties. The intrinsic properties of standing dead grass do not change when the grass is mowed. But the behavior of a fire through that fuel is different due to the arrangement of the fuel particles, an extrinsic property. Similarly, the intrinsic properties of a log don't change when it is split into kindling, but the wood burns quite differently due to a change in the surface-area-to-volume ratio.

Quantity Fuel loading is the ovendry weight of fuels in a given area, often expressed in tons/acre or lb/ft^2. Expressing loading on an ovendry basis

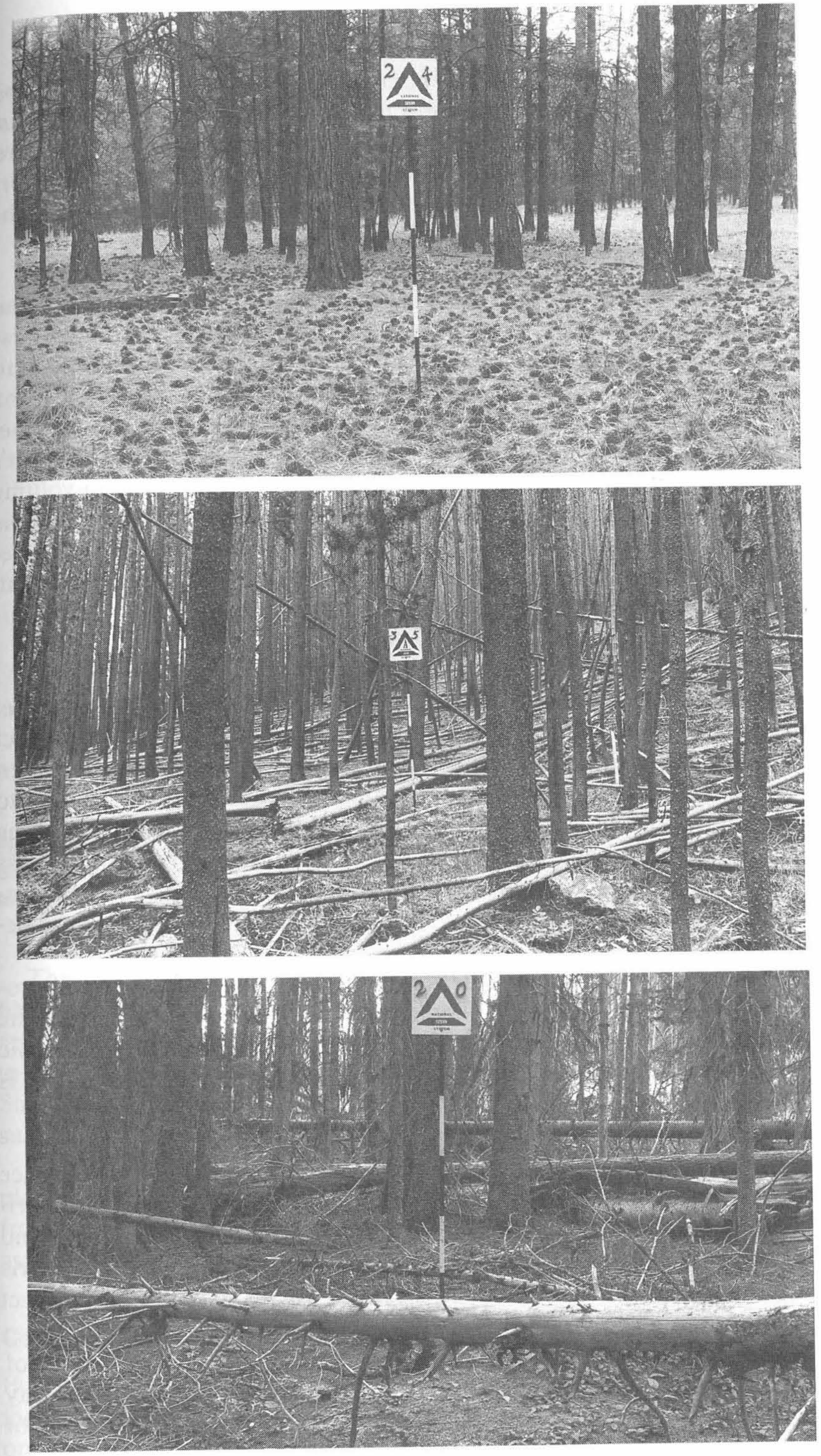


Figure 3.3. *Loadings of downed woody material vary widely as illustrated: 1 ton/acre in a ponderosa pine stand (top); 12 tons/acre in a lodgepole pine stand (middle); and 40 tons/acre in a spruce-fir stand (bottom).* From Brown and See (1981).

allows fuel state (moisture content) to be considered separately from fuel type. Fuel loading varies greatly for different fuel complexes (Figure 3.3). A grass type may be 1 to 5 tons/acre, while logging slash may be 30 to 200 tons/acre. The quantity of ground fuel is often specified in terms of duff depth. Ovestory fuel quantity is sometimes specified as trees per acre or as the weight of the needles.

Size and Shape It is clear from the experience of starting a campfire that small fuels ignite and sustain combustion easier than large pieces of fuel. Less heat is required to remove fuel moisture and raise a small fuel particle to ignition temperature. Thus it is the fine dead fuels that carry the flaming fire front. The size of a fuel particle is often given as the ratio of the surface area of a fuel to its volume (ft^2/ft^3). For fuels that are long with respect to their thickness it's $4/d\ ft^{-1}$; the higher the ratio, the finer the particle. The surface-area-to-volume ratio of a $\frac{1}{4}$-inch-diameter twig is $200\ ft^{-1}$, while that of a 6-inch-diameter log is $8\ ft^{-1}$. This is a meaningful measure of fuel particle size because of its relationship to rates of change in fuel temperature and in moisture content. There are also relationships between surface-area-to-volume ratio and ignition time and spread rate.

Compactness Compactness can be thought of as the spacing between fuel particles. The closeness and physical arrangement of the fuel particles affect both ignition and combustion. In most cases, slower spread rates occur when fuels are compacted. Loosely compacted fuels will normally react faster to moisture changes and have more oxygen available for combustion. Packing ratio is a function of depth and load as well as particle size. Compactness relates to the spacing of fuel particles and affects ignition time and combustion through its influence on oxygen supply and radiant energy transfer between particles.

Bulk density, the weight per unit volume of a fuel complex, is an appropriate measure of porosity of a fuel complex. It fails to precisely express the amount of fuel complex occupied by actual fuel volume because the specific gravity of fuel is disregarded. Thus, only weight, and not volume of fuel, is incorporated in an expression of bulk density.

Arrangement The way that fuel particles are arranged has a great influence on fire behavior. Arrangement includes the orientation of fuel particles (horizontal or vertical) and the spatial relationship between particles. Grass and brush are vertically oriented fuel types, while timber litter and logging debris are horizontally oriented. Relationships between load and depth with respect to arrangement are shown in Figure 3.4.

In the case of large dead logs, arrangement can make the difference of whether the fuel burns or not (Figure 3.5). Arrangement also refers to the way that the fuel particles are mixed, the live-to-dead ratio, and the relationship of fine dead fuels to the rest of the fuel complex.

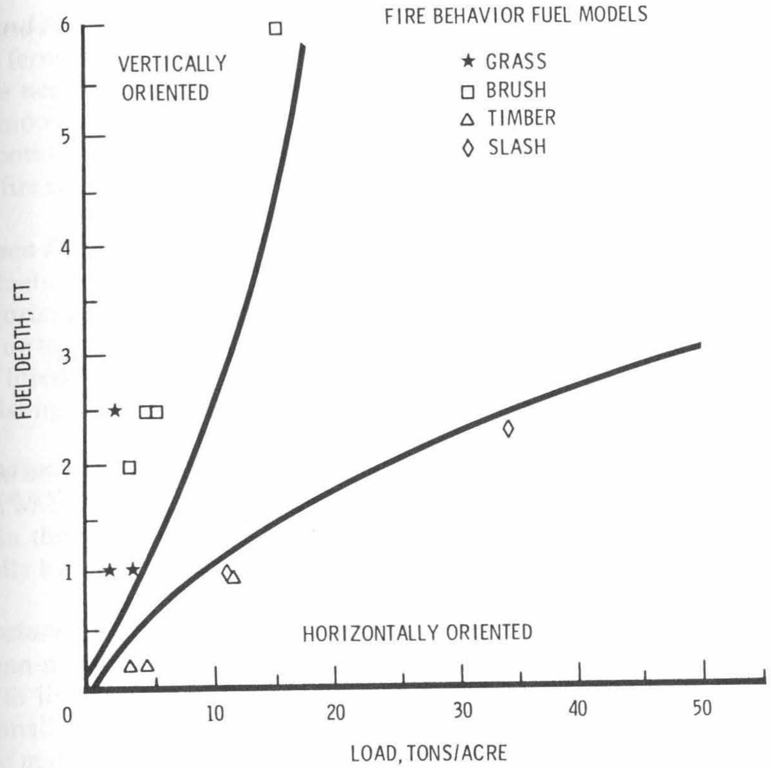


Figure 3.4. *Fuel depth vs. load for the standard fire behavior fuel models (see Figure 3.8). Grasses and shrubs are oriented vertically while timber, litter, and slash are oriented horizontally.* From Anderson (1982).

The arrangement of fuels in the horizontal plane can influence fire behavior and can be a determining factor in whether the fire will burn or spread at all. If the open areas are barren and void of fuels, it will be difficult for a fire to travel from one fuel island to another without strong winds and spotting. Similarity, the horizontal continuity of crown fuel can determine whether a sustained crown fire is possible.

The vertical arrangement of fuels influences which parts of the fuel complex are included in the fire. A fuel ladder (Figure 3.6) can transport the fire from the surface fuel to the crowns, with a significant change in fire behavior as described in Chapter 2.

Components

Fuel components can be categorized according to vertical layer—ground, surface, and aerial or crown fuel (as shown in Figure 3.6). This grouping is based on significant differences in the behavior of fire through each layer.

Figure 3.5. *Fuel arrangement determines how a group of large logs will burn. A pile of logs creates a hot fire because the burning logs radiate heat to each other. When the pile is broken up, radiant heat transfer is greatly reduced.* From Barrows (1951).

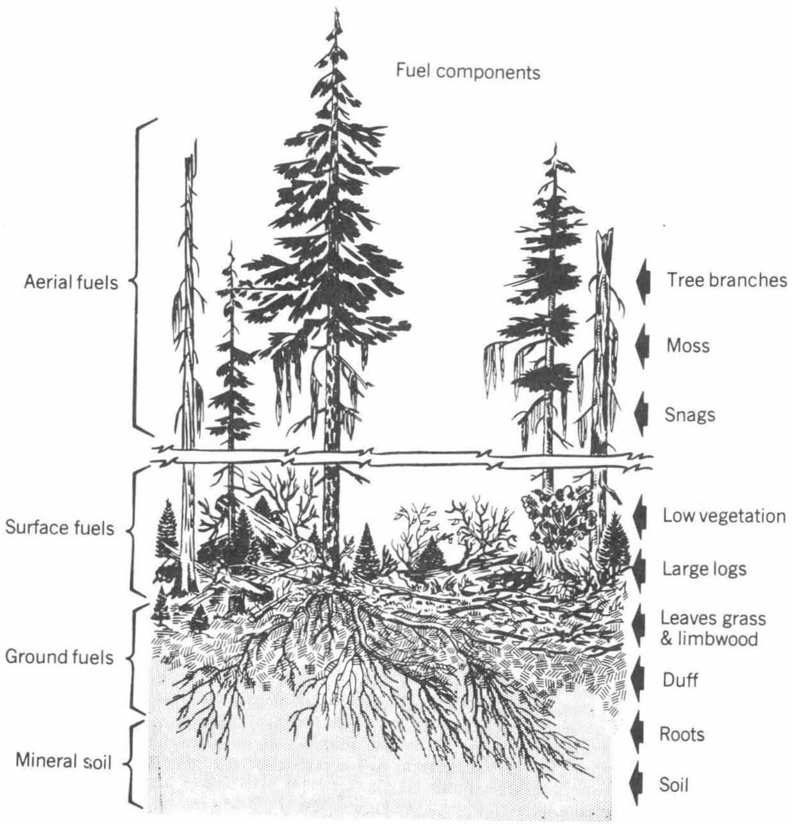


Figure 3.6. *Fuel components are categorized according to ground, surface, and aerial or crown fuel.* From Barrows (1951).

Ground Fuel Ground fuels include duff, roots, and rotten buried logs. *Duff* is the fermentation and humus layers of the forest floor. The top of the duff is where needles, leaves, and other castoff vegetation material have begun to decompose. Individual particles usually will be bound by fungal mycelium. The bottom of the duff is mineral soil. Because of the compactness of ground fuel, fire spread will be slow, typically burning by smoldering combustion.

Surface Fuel Since most wildland fires ignite in and are carried by the surface fuels, this fuel level has received the most emphasis. Surface fuels can be categorized according to physical characteristics of the vegetation: standing trees up to about 6 ft, shrubs, herbaceous vegetation (grasses and forbs), forest floor litter, and downed woody material (Figure 3.7). *Litter* is the surface layer consisting of freshly fallen leaves, needles, twigs, stems, and bark.

Aerial or Crown Fuel Crown fuel includes overstory trees and large shrubs. Even when the canopy is not included in the fire, it affects the behavior of the fire in the surface fuel. Timber stands with open canopies, for example, usually have a faster spreading surface fire than closed stands.

Structures Wildland fuel technically includes vegetative material, but human-made structures might also be considered a fuel component. People like to live in homes surrounded by natural vegetation. Thus homes occasionally become part of the fuel involved in a wildland fire. Use of natural forest materials in construction makes the structure more of a "wildland fuel," susceptible to becoming involved in and even contributing to a wildfire.

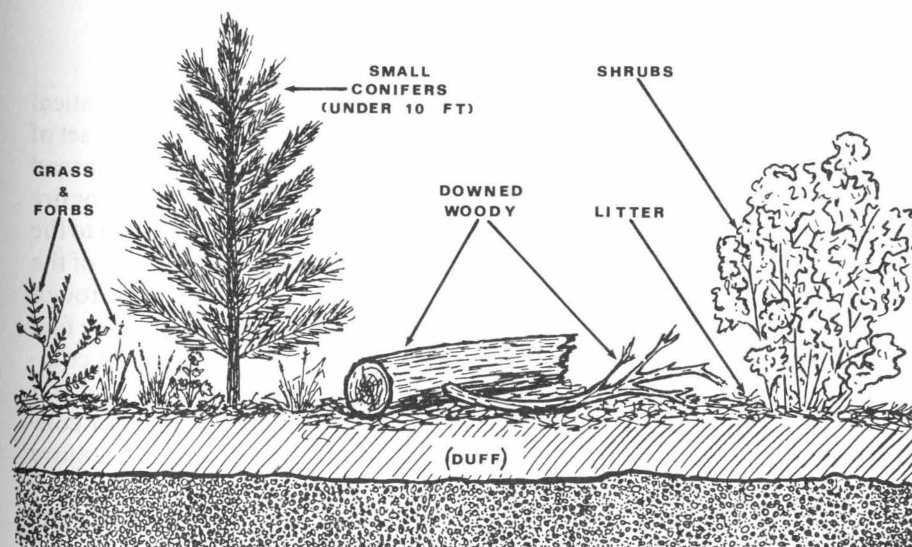


Figure 3.7. *Vegetative components included in surface fuel.* From Brown and others (1982).

Complexes

A fuel complex is an association of fuel components based on vegetation communities. These biological systems are described in various ways such as cover type or habitat type. It is difficult to relate these directly to fuel. Fuel generally occurs as mosaics, rarely unbroken and continuous over large areas. Vegetation types in the United States range from black spruce and feather moss in Alaska to sawgrass in Florida and Hawaii, and from wetland vegetation in the southeast to desert plants in the southwest. A description of these vegetation communities as a fuel complex depends on fuel properties and components that have an effect on wildland fire.

A rangeland fuel complex, for example, may consist of only grass or of a combination of grass and brush. A conifer timber fuel complex consists of overstory trees and an understory that can be just litter and grass or might include heavy dead and down fuel and brush. Two fuel complexes, aspen and palmetto–gallberry, are discussed as selected examples at the end of the chapter.

3.3 FUEL CLASSIFICATION

There is essentially infinite variability in fuel, in kind, amount, size, shape, position, and arrangement. The need to organize fuel description information has resulted in various methods of fuel classification. Classification schemes have traditionally depended on the aspect of fire that is under consideration. The fuel classification schemes described here are fuel models, inventory, photo guides, and Canadian fuel types.

Fuel Models

A fuel model is a stylized and simplified description of fuel for a mathematical fire behavior model. A fire model is a set of equations; a fuel model is a set of numbers that describe the fuel for the fire model. Rothermel's fire spread model was described at the end of Chapter 1; application of that model for fire behavior prediction was given in Chapter 2. Providing fuel information to the fire model in terms of a fuel model makes the complex set of equations of the fire model easy to use. Because the fire model calculates rate of spread through surface fuels, that is the aspect of the fuel complex that is included in the fuel model. The set of 13 standard fuel models shown in Figure 3.8 is most commonly used. Two of the programs in the BEHAVE fire behavior prediction and fuel modeling system allow a person to develop custom fuel models for conditions that are not covered by the 13. Those procedures do not require detailed field inventory.

The differences in fire behavior are basically related to the fuel load and its distribution among the fuel particle size classes. Fuel model parameters include load and surface-area-to-volume ratio for each class (live and dead),

Fuel model	Typical fuel complex	Surface-area-to-volume ratio(ft^{-1})/ fuel loading (tons/acre)[1]				Fuel bed depth	Moisture of extinction dead fuels	Characteristic surface area-to-volume ratio	Packing ratio
		1-h	10-h	100-h	Live				
						Ft	Percent	Ft^{-1}	
	Grass and grass-dominated								
1	Short grass (1 ft)	3,500/0.74	—	—	—	1.0	12	3,500	0.00106
2	Timber (grass and understory)	3,000/2.00	109/1.00	30/0.50	1,500/0.50	1.0	15	2,784	.00575
3	Tall grass (2.5 ft)	1,500/3.01	—	—	—	2.5	25	1,500	.00172
	Chaparral and shrub fields								
4	Chaparral (6 ft)	2,000/5.01	109/4.01	30/2.00	1,500/5.01	6.0	20	1,739	.00383
5	Brush (2 ft)	2,000/1.00	109/0.50	—	1,500/2.00	2.0	20	1,683	.00252
6	Dormant brush, hardwood slash	1,750/1.50	109/2.50	30/2.00	—	2.5	25	1,564	.00345
7	Southern rough	1,750/1.13	109/1.87	30/1.50	1,500/0.37	2.5	40	1,562	.00280
	Timber litter								
8	Closed timber litter	2,000/1.50	109/1.00	30/2.50	—	.2	30	1,889	.03594
9	Hardwood litter	2,500/2.92	109/0.41	30/0.15	—	.2	25	2,484	.02500
10	Timber (litter and understory)	2,000/3.01	109/2.00	30/5.01	1,500/2.00	1.0	25	1,764	.01725
	Slash								
11	Light logging slash	1,500/1.50	109/4.51	30/5.51	—	1.0	15	1,182	.01653
12	Medium logging slash	1,500/4.01	109/14.03	30/16.53	—	2.3	20	1,145	.02156
13	Heavy logging slash	1,500/7.01	109/23.04	30/28.05	—	3.0	25	1,159	.02778

[1]Heat content = 8,000 Btu/lb for all fuel models.

Figure 3.8. *Fuel model parameters and calculated fuel bed descriptors for the standard 13 fire behavior fuel models.* From Andrews (1986).

fuel bed depth, and moisture of extinction. Moisture of extinction is the moisture at which the fire will not spread. Other parameters required by the fire model are generally held constant: density, heat content, and mineral content. Characteristic surface-area-to-volume ratio and packing ratio are calculated from the other parameters.

Fuel models are described in terms of fire behavior first and vegetation type second. The choice of fuel model is made through photographs and description provided by Anderson (1982) or by a dichotomous key. Following is a description of fuel model 6, often called "dormant brush:"

> Fires carry through the shrub layer where the foliage is more flammable than fuel model 5, but this requires moderate winds, greater than 8 mi/h (13 km/h) at midflame height. Fire will drop to the ground at low wind speeds or at openings in the stand. The shrubs are older, but not as tall as shrub types of model 4. A broad range of shrub conditions is covered by this model. Fuel situations to be considered include intermediate stands of chamise, chaparral, oak brush, low pocosin, Alaska spruce taiga, and shrub tundra. Even hardwood slash that has cured can be considered. Pinyon–juniper shrublands may be represented but may overpredict rate of spread except at high winds, like 20 mi/h (32 km/h) at the 20-foot level.

In addition to static fire behavior fuel models, dynamic fuels models have been developed for some fuel types, accounting for a change in fuel type over time. An example of a dynamic fuel model for palmetto–gallberry is given at the end of the chapter. Eleven of the 13 fire behavior fuel models were first developed for the 1972 National Fire Danger Rating System (NFDRS). The 1978 revision of NFDRS included equations to reflect the influence of heavy dead fuels; thus a new set of 20 fuel models was developed, some including up to 8-in.-diameter logs. The original 13 fuel models continue to be used for fire behavior prediction.

Inventory

Brown and others (1982) have developed comprehensive procedures for inventorying living and dead surface vegetation for fuel appraisal. They describe how to conduct field work and estimate loading of downed woody material, forest floor litter and duff, herbaceous vegetation, shrubs, and small conifers. Weights by species are determined for shrubs and small conifers. Coverage of shrubs and herbaceous vegetation is estimated. The several sampling methods involve counting and measuring the diameters of downed woody pieces along a transect, comparing quantities of litter and herbaceous vegetation against standard plots that are sampled and weighed, tallying shrub stems by basal diameter classes, tallying conifers by height classes, and measuring duff depth.

Photo Guides

Photo guides for appraising fuels have been developed for specific fuel types including recent logging slash, aged slash, and natural dead and downed fuel (see Figure 3.24). Many of the guides are for appraising downed woody fuel, to rate the potential fire behavior in the fuel shown in each photo, giving loading and size class distribution of downed woody fuel. Information accompanying each photo includes information such as forest cover type, habitat type, age of overstory, elevation, aspect, and information from a dead-and-down fuel inventory. In addition, fire behavior for an "average bad" fire weather situation is often included. The elements rated include rate of spread, intensity, torching, crowning, resistance to control, and an overall fire potential rating. Various methods have been used to predict potential fire behavior for the various photo guides, including a resistance to control rating, Rothermel's fire model, and the experienced judgment of fuel and fire behavior experts.

Group / Identifier	Descriptive name
Coniferous	
C-1	Spruce–lichen woodland
C-2	Boreal spruce
C-3	Mature jack or lodgepole pine
C-4	Immature jack or lodgepole pine
C-5	Red and white pine
C-6	Conifer plantation
C-7	Ponderosa pine–Douglas-fir
Deciduous	
D-1	Leafless aspen
Mixedwood	
M-1	Boreal mixedwood–leafless
M-2	Boreal mixedwood–green
M-3	Dead balsam fir mixedwood–leafless
M-4	Dead balsam fir mixedwood–green
Slash	
S-1	Jack or lodgepole pine slash
S-2	White spruce–balsam slash
S-3	Coastal cedar–hemlock–Douglas-fir slash
Open	
O-1	Grass

Figure 3.9. *Canadian Fire Behavior Prediction system fuel types.* From Forestry Canada Fire Danger Group (1992).

Canadian Fuel Type

Fuel type for the Canadian Fire Behavior Prediction (FBP) system has been defined as "an identifiable association of fuel elements of distinctive species, form, size, arrangement, and continuity that will exhibit characteristic fire behavior under defined burning conditions." More specifically, a fuel type is a fuel complex of sufficient homogeneity and extending over an area of sufficient size that equilibrium fire behavior can be maintained over a considerable time period. The FBP system organizes fuel types into five major groups, with a total of 16 discrete fuel types. Fuel types in the FBP system are described qualitatively, rather than quantitatively, using terms describing stand structure and composition, surface and ladder fuels, and the forest floor cover and organic (duff) layer. FBP system fuel type descriptions do not rigorously or quantitatively follow forest inventory patterns; however, knowledgeable fire managers can develop methods to classify their land base and vegetation data for fire planning. A list of FBP system fuel types is given in Figure 3.9. Following is a description of Fuel Type C-3 (Mature Jack or Lodgepole Pine):

> This fuel type is characterized by pure, fully stocked (1000–2000 stems/ha) jack pine stands that have matured at least to the stage that crown closure is complete and the base of live crown is substantially separated from the ground. Dead surface fuels are light and scattered. Ground cover is basically feather moss over a moderately deep (10 cm) compact organic layer. A sparse conifer understory may be present.

3.4 FUEL MOISTURE

The preceding sections on fuel description and classification relate to fuel type. We now discuss the state of the fuel—fuel moisture. Potential fuel was defined as the fuel that could burn under extreme conditions. The amount of fuel that is available for combustion in a given fire (available fuel) is determined largely by the amount of water in the fuel (fuel moisture).

The process by which fuel moisture affects combustion was covered in Chapter 1. Water is a heat sink; it must be boiled away before the fuel can be heated to ignition temperature. If the required heat is more than is available, then there is no fire. 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 spread at high intensities.

Fuel moisture affects all aspects of fire behavior and fire effects: spread rate, intensity, smoke production, fuel consumption, and plant mortality. In addition, moisture is such a critical factor in assessing fire potential that moisture calculations are the foundation of fire danger rating systems (discussed in Chapter 4).

Fuel moisture is a product of the cumulative effects of past and present weather events. In addition, moisture content of live vegetation is affected by

biological processes. Fuel moisture can change in minutes in the case of lichen, or weeks as in large logs, or over the season for greenup and curing of live vegetation. Fuel moisture, in fact, changes in all time scales: abrupt, diurnal, seasonal, annual, and even at the successional scale, if we consider the effect of changing fuel and weather (global climate change) on moisture.

Moisture varies in space as well as in time. The complex arrangement of fine fuel particles on the forest floor can produce wide variations in the moisture content throughout the fuel layer because of varying degrees of exposure of individual fuel particles to wetting and drying forces. Variation within a live plant at a point in time results from factors such as exposure to the sun and foliage age. There can even be significant variability within a single fuel element. The moisture content of a large log is never uniform. Figure 3.10 shows the variation in moisture content within a log. The reality of this variability must be recognized when a measured or calculated fuel moisture value is cited.

Moisture content is generally expressed as a percentage on an ovendry weight basis. The fraction of moisture content is the weight of the water (initial fuel weight minus dry weight) divided by the weight of the ovendry material. Dead fuel moisture can be a low as 1 or 2% in deserts. Fiber saturation is 30 to 35%. Sound wood at higher moistures has water in cracks, in pores, or in spaces between cells. Decayed wood has many open spaces between woody fibers and so can hold water like a sponge up to 300% or more. Live fuel moisture generally ranges from about 50 to 300%, but can be over 1000%. Duff moisture content is highly variable, up to several hundred percent. In some situations, seemingly wet ground fuel can burn.

Dead Fuel Moisture

Process The amount of water in a fuel particle is always changing, depending on how wet or dry the environment is. Fuel can gain moisture either through liquid water or through water vapor. The process of fuel drying is accomplished by evaporation to the environment.

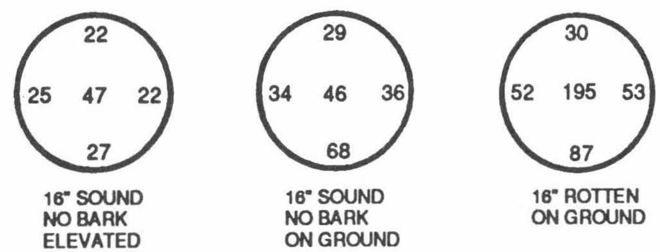


Figure 3.10. *Moisture content varies within a log. Percentage moisture content at top, bottom, center, and sides of three selected logs. The moisture contents are averages of measurements taken at 1-, 2-, 3-, 5-, and 7-ft intervals.* From Reinhardt and others (1991).

The hygroscopic nature of the materials making up the dead cell walls makes it possible for them to adsorb water vapor from the air. The water molecules that penetrate and are held to the cell walls and the few molecular layers that adhere to the cell walls are called bound water. The amount of bound water at the fiber saturation point for most plant fuels is in the range of 30 to 35% of dry fuel weight. Adsorption and desorption processes are due to diffusion at locations in the fuel that contain bound water but no free liquid water.

Many processes occur at the fuel surface; these events largely determine transfer within the fuel. Heat loss is due to conduction away from the surface and to radiative cooling. Heat gains are due to solar radiation and convective heating by the ambient air. The amount of liquid water on the fuel surface is affected by rainfall and by condensation and evaporation. These processes control surface gain or loss of moisture above the fiber saturation point.

Influences Dead fuel moisture is a result of the environment; it is affected by all three legs of the fire environment triangle: fuel, weather, and topography. The primary influence is weather. The way that fuels react to weather changes depends on the composition and size of the fuel as well as location. Topography affects the microclimate and determines the amount of sun that the fuel receives.

Characteristics of fuel that affect its moisture include the composition of the material (needles, leaves, grass, duff, sound wood or rotten wood) and the size of the fuel (diameter of wood, depth of duff). In addition, the presence of surface layer, such as bark or wax, on the fuel affects the way it gains and loses moisture.

The location of the fuel is also a factor—whether it is on or above the ground and whether it is under a canopy or in the open. In an open area, exposure to direct solar radiation results in a lower average daytime moisture content and a greater amplitude to the moisture content cycle than under an adjacent canopy. Following rain, material on the ground is subject to a more humid environment, resulting from evaporation of moisture from the duff layer. When dry, however, absorption of solar radiation raises the duff surface temperature, thereby lowering surface relative humidity, which, in turn, reduces the moisture content of fuels on the ground. Dead fuels attached to the plants are exposed to different conditions than those on the ground (e.g., frosted leaves on brush vs. leaf litter on the ground).

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% 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 wet. Reverse conditions 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 moisture conditions that are higher at the surface than lower in the duff.

The weather elements that affect dead fuel moisture content are rain, wind, solar radiation, and the temperature and humidity of the air. When the temperature reaches the dew point, water condenses on the fuel. Past rain and snow affect the moisture of soil and ground fuels, which thereby affect the moisture of fuels laying on them. Wind can have both a drying and a wetting effect. For fuels in the sun the wind's cooling action can offset its drying action.

Solar radiation has long been recognized as an important influence on fuel moisture due to increase in fuel temperature. The intensity of sunlight varies with time of day, time of year, slope, aspect, latitude, and haziness of the atmosphere.

Equilibrium Moisture Content The equilibrium moisture content (EMC) 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. A dry fuel in a moist environment reaches equilibrium at a lower value than a moist fuel approaching the same equilibrium point from above (Figure 3.11). EMC is a condition wherein a fuel is very close to being in equilibrium with the moisture of the air immediately surrounding it. At this stage, no further significant net exchange of moisture will take place. Actually, in nature this is a transitory situation, since the atmospheric conditions surrounding the fuel seldom remain stable for long.

Figure 3.11 illustrates how the moisture content of fine forest fuels is influenced by relative humidity, and that different fuels react differently to environmental changes. Air temperature also affects EMC: EMC decreases as air temperature increases.

Timelag Dead fuels can be classified according to the time it takes the fuel to adjust to changes in the environment (Figure 3.12). When a change occurs, the moisture moves toward a new equilibrium. How quickly these fuels gain or lose moisture in response to wetting or drying cycles establishes their response time. Timelag is an expression of the rate at which a given fuel approaches its equilibrium moisture content. Timelag interval, or response time, is defined as the time required for dead fuel to lose approximately 63% $(1 - 1/e)$ of the difference between its initial moisture content and equilibrium moisture content in an atmosphere of constant temperature and humidity. The duration of these time periods is a property of the fuel. Timelag can be expressed in minutes or hours or days. For clarity, hours are generally used.

The average timelag period varies with the size and other factors of the fuels. For extremely fine fuels the average period may be a matter of minutes, while for logs it ranges upward to a month or more. 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 of about 36 days. A 2-inch

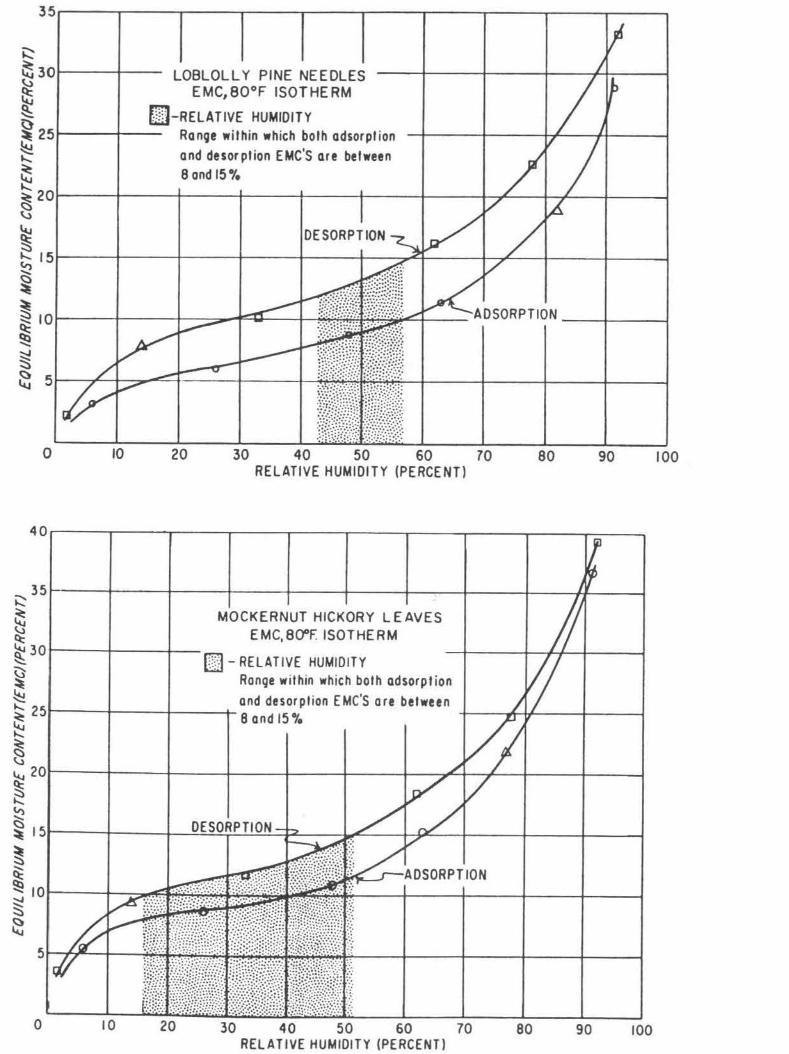


Figure 3.11. *Equilibrium moisture content (EMC) during desorption and adsorption cycles of fine fuel materials found in forests of the southeastern United States. The range of relative humidity that gives fuel moistures from 8 to 15% are shaded.* From Blackmarr (1972).

litter bed with an average timelag period of 2 days can be considered the equivalent, in moisture response characteristics, of dead branchwood ($\frac{1}{4}$ inch diameter) having a similar timelag period if there is no significant moisture exchange between the litter and the soil.

The concept of timelag was developed by Byram in 1963 (unpublished) and expanded by Fosberg (1970). The resolution was appropriate for fire danger rating needs at that time. Fuels were grouped into four timelag classes: up to 2 h, 2 to 20 h, 20 to 200 h, and greater than 200 h. Class midpoints then were taken

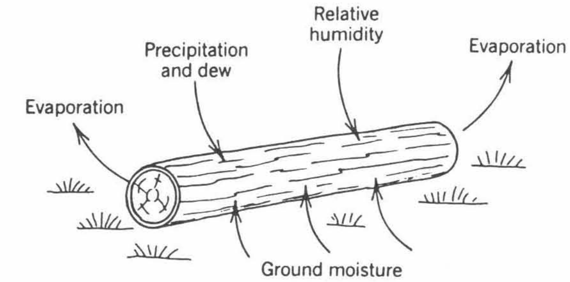


Figure 3.12. *Factors influencing moisture exchange in wildland fuels.*

as the title for each timelag class: 1 h, 10 h, 100 h, 1000 h. Although this is an oversimplification, the terminology continues to be used. A direct equivalence is made to diameter and timelag: 1 h = 0–$\frac{1}{4}$ inches; 10 h = $\frac{1}{4}$–1 inch; 100 h = 1–3 inches; 1000 h = >3 inches diameter.

Applying the strict timelag classification to fire behavior prediction can cause errors. Anderson (1990b) found a great variation in response times for fine forest fuels (Figure 3.13). Timelags for grasses, mosses, and lichens were on the order of 2 to 4 h, weathered conifer needle litter was 2 to 14 h, and recently cast conifer needles had response times of 5 to 34 h. Calling these 0- to $\frac{1}{4}$-inch-diameter fuels "1-h timelag fuels" is obviously misleading.

Anderson (1985) showed the effect of timelag (Figure 3.14). A repeating diurnal cycle was established from August weather data for O'Neill, Nebraska. This diurnal cycle was used to establish the forcing EMCs experienced during each 30-min period in the 24 hours from 2 P.M. to 2 P.M. The significant feature is not how much lag there is in moisture behind the weather condition, but the reduction in sensitivity to change. This results in a misrepresentation of afternoon fuel moisture. Although the EMC forcing function ranges from 14.8 to 6.1%, the range for grasses drops to 6.3%, and for the slowest responding needles the range is only 0.9%. Fine fuels with long timelags will take long periods of dry weather to reach the low moisture contents that can be reached in 1 day by fuels with true 1-h timelags.

Fine dead fuel moisture is an important factor in determining fire behavior, particularly the rate of spread of a spreading surface fire. An example is the hourly variation for two days during the Yellowstone National Park fires of 1988. Low fuel moisture at night allowed active burning through the night (see Figure 3.2b).

Reindeer lichen is among the fastest drying of forest fuels. Péch (1989) showed that when submerged in water it can increase in moisture to 400%, and when drying in shade it can lose 63% of its free moisture in less than 2 h. Reindeer lichen is a major surface fuel in vast regions of the boreal and subartic forests.

The moisture of larger dead fuel affects the behavior of the fire behind the flaming front. The moisture content affects the burnout rate and the amount of

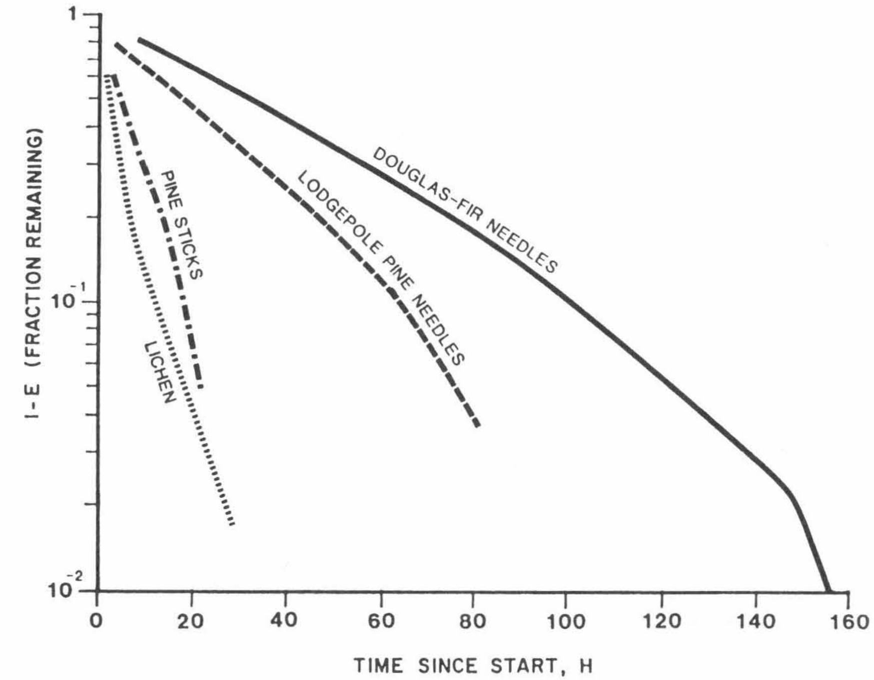


Figure 3.13. *Response time for moisture change for witch's hair lichen, $\frac{1}{2}$-inch ponderosa pine sticks, lodgepole pine needles, and Douglas-fir needles.* From Anderson (1990b).

fuel that is consumed. When fuels are very dry there can be 100% consumption where all that is left of logs is a tell-tale line of ashes (see Figure 3.1b).

The limiting rate at which water diffuses into wood is less than most rainfall rates; excess rain is shed by solid wood. The moisture content of large roundwood is thus related to rainfall duration. In contrast, ground fuel retains much of the excess water in the fuel bed structure; duff moisture content is related to rainfall amount.

Live Fuel Moisture

Wildland fires are often influenced by living vegetation. Grasses, ferns, shrubs, mosses, herbaceous plants, and trees may either contribute actively to the energy of a fire, or they may serve as a heat sink and retard fire propagation and intensity.

While dead fuel moisture is a function of weather conditions, live fuels exhibit seasonal changes in moisture in accordance with physiological processes such as spring flushing and fall curing. There is significant variability in plant phenology, morphology, and physiology. In a study on summer moisture contents of understory vegetation in northeastern Minnesota, for example, Loomis and others (1979) found averages of seasonal moisture content percentage ranging from 138% for Labrador tea to 1027% for bluebead lily.

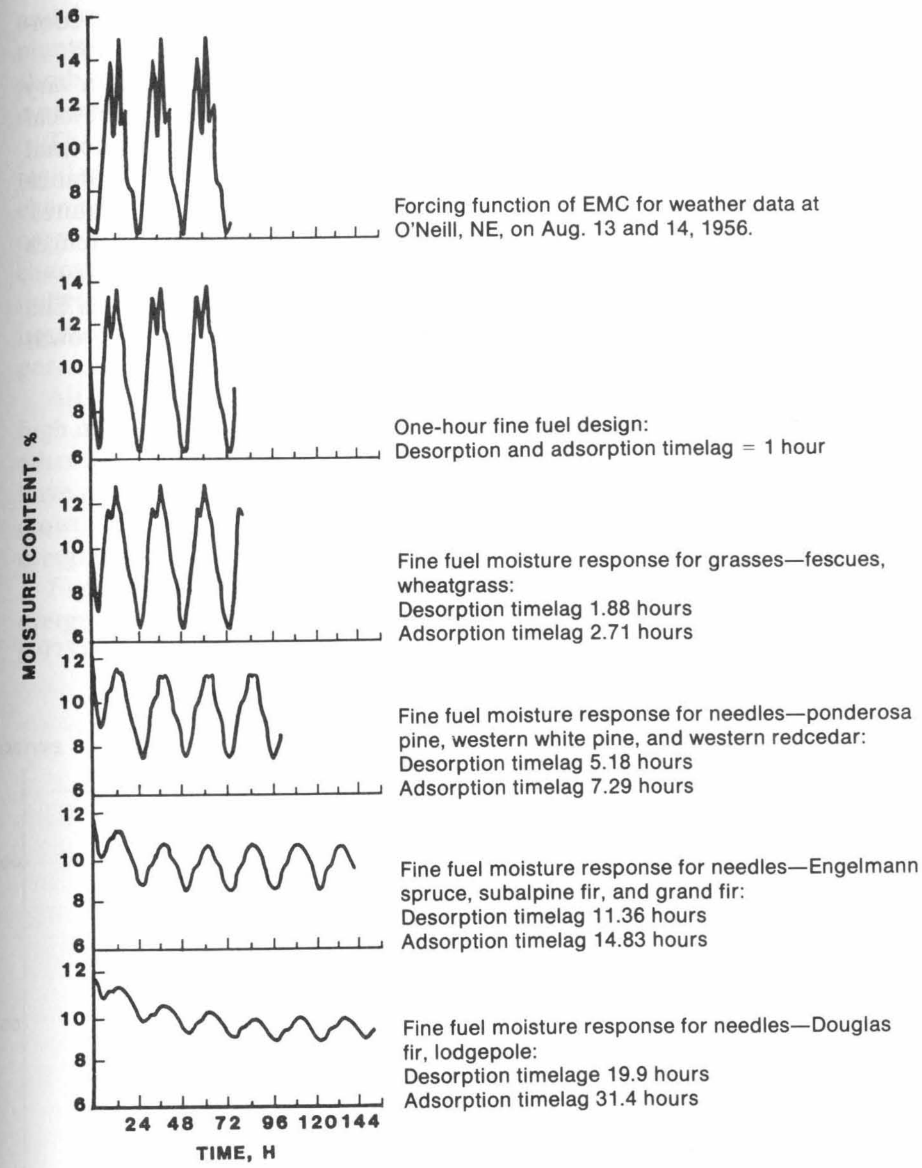


Figure 3.14. *Not all fine forest fuels respond to moisture changes with 1-h timelags. As the timelag increases, the response becomes slower and less sensitive.* From Anderson (1985).

Water movement in a forest is a function of both physical and physiological factors. Physical factors such as precipitation and soil storage provide the water supply, while atmospheric evaporative force supplies the demand. The tree is the transport system from the soil to the atmosphere; however, this transport is controlled by physiological responses by the tree to the physical environment. Running (1978) described a general perspective of the components of a process-oriented model for live fuel moisture (Figure 3.15).

The moisture content of living plant foliage of wildland species can vary markedly with seasonal changes. The patterns 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 snowpack, or the occurrence of unseasonably warm or cool temperatures. Elevation and aspect affect local microclimate and produce local differences in seasonal development of many plant species.

Moisture content of new foliage is highest at the time of emergence. The moisture normally declines from the peak quite rapidly during leaf growth

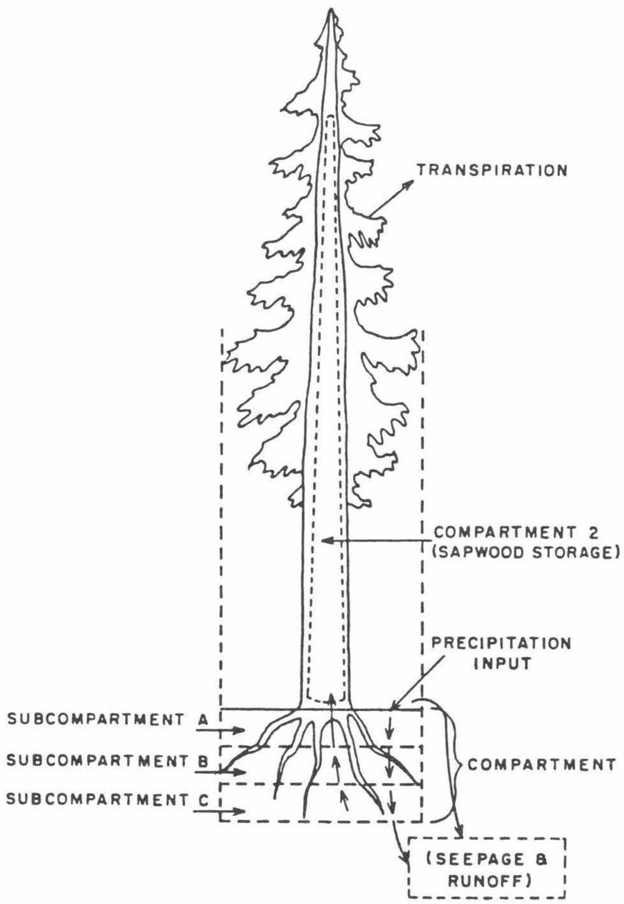


Figure 3.15. *General perspective of the components of a process oriented model for live fuel moisture. Compartment 1 is defined as water available to the tree from soil within its rooting zone. Compartment 2 is defined as water available from transpiration stored within the sapwood of the tree.* From Running (1978).

and development, then somewhat more slowly to a terminal value. In annual plants, the end result is the death of the plant. In perennials and 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.

The decrease in plant foliage moisture is usually not smooth, but an irregular succession of ups and downs. Foliage moisture content may even change during the course of the day. 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 the ability of the leaf to open or close the leaf pores and thus regulate the rate of transpiration to the atmosphere.

All deciduous foliage is the current year's growth and maintains relatively high moisture content during most of the growing season. Evergreens, on the other hand, 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% or more of the total evergreen foliage volume.

Figure 3.16 shows the seasonal variation in the moisture content of both evergreen and deciduous shrubs in North Carolina. Blackmarr and Flanner (1975) observed moisture content cycles in new foliage, old foliage (for ever-

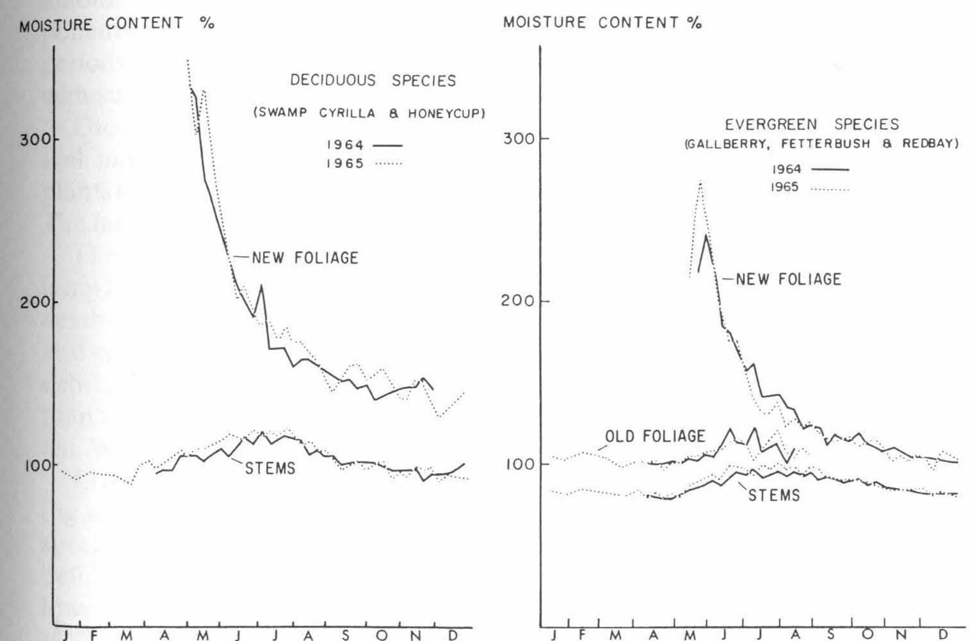


Figure 3.16. *Annual moisture content cycles in selected deciduous and evergreen pocosin shrubs during two years showing differences in stems and new and old foliage.* From Blackmarr and Flanner (1975).

green species), and stems. Most species exhibited a rapid buildup of moisture content as new growth resumed in the spring. Moisture contents declined rapidly during the first few weeks of growth, then tapered off gradually toward the end of the growing season. Each species had a characteristic pattern of moisture content variation that was relatively constant over two growing seasons. Evergreen shrubs usually had lower moisture contents than deciduous shrubs at any given time of the year.

The moisture content of old conifer foliage decreases and reaches a minimum in spring and then gradually increases to a maximum later in the summer. The timing of both the flushing of new conifer foliage and the minimum moisture content of the old foliage varies with altitude, occurring earlier at lower elevations and later at higher elevations. Otherwise, the general trends in foliar moisture appear to be similar from year to year. Figure 3.17 shows the mean seasonal moisture variations in old foliage for jack pine and black spruce in central Alberta, Canada.

The low preflushing moisture content of conifer foliage in the spring is associated primarily with the increase in dry matter, which subsequently declines as the moisture percentage increases. This latter decline in dry matter

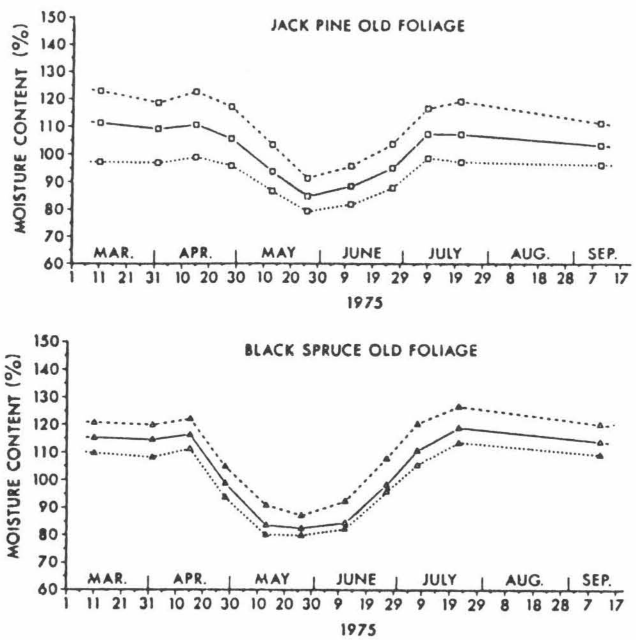


Figure 3.17. *Mean seasonal moisture variations in old foliage for Jack pine and black spruce for foliage ages 1 year old (dashed line), 2 years old (solid line), and 3+ years old (dotted line). Each of the mean values plotted is based on ovendry weights of five samples.* From Chrosciewicz (1986).

coincides closely with the initiation of new growth and appears to be similar quantitatively to the dry matter increase in new foliage. Seasonal variations in foliar moisture, however, appear to be affected more by changes in the actual water content than by the changes in ovendry weight.

Annual grasses are much more sensitive to seasonal and short-term weather variations than are most other live wildland fuels. Shallow-rooted grasses depend primarily on adequate surface soil moisture for full top development. Annuals mature, produce seed, and begin to cure and dry. 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. Annual grasses may die and 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. The principal differences in moisture content result from a later maturing date and a slower rate and longer period of curing (see Figure 3.27).

Drought

From the viewpoint of wildland fire, drought is important in that it affects the amount of available fuel. Because of their low moisture content, fuel components that might not otherwise burn become available fuel during during periods of drought. The result is more intense fires and increased difficulty with suppression efforts.

Drought effects go beyond the normal seasonal trends in both live and dead fuel moisture described above. Prolonged moisture deficiency can cause plants to die, large logs to lose moisture to their center, and deep duff to dry out. The lack of soil moisture can cause stress in live plants.

The moisture of the fine fuels that control fire spread through surface fuels is not affected by drought. But additional fine dead fuels might be added due to death of live plants and foliage. The moisture content of large fuel components and ground fuel are dependent on long-term drying processes. Large woody debris can actually sublime moisture in cold winter when snow cover is less than normal, causing early spring moisture contents much lower than expected. When dry, these fuels can add significantly to the intensity of a fire.

Live vegetation responds to drought in a variety of ways. Particularly striking are the variations found in the drought-resistant brush and chaparral 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%. 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.

Moisture Assessment

There are several ways to assess fuel moisture content. Fuel moisture values can be obtained through direct measurement, through inference from some other variable, or through calculation based on observable weather elements.

Direct Measurement Fuel moisture can be obtained from a sample of the material. The sample is weighed, dried, then weighed again (Figure 3.18). The ovendry moisture content is calculated. Sampling might be used when there is no good method of calculation or inference. It is important to use sound sampling techniques. A few pieces of live grass in a dead grass sample can greatly bias the results. There is always a lot of variability at a site. A good sampling scheme must be determined so that a good estimate of moisture might be obtained. The moisture of live leaves and needles can change during a day and can vary within a plant (Figure 3.19).

There are instruments that read moisture content directly. Fuel moisture probes, which use electric resistance to measure moisture content were developed for lumber and are sometimes used for wildland fuel. The probe is activated by pressing its two electrodes firmly into a sample. Probes can give quick estimate in the field when time doesn't allow for sampling. Again, the issue of variability on a site and within a fuel element must be considered. In addition, because the probes were developed for use with lumber, they can measure only a limited range of moisture contents.

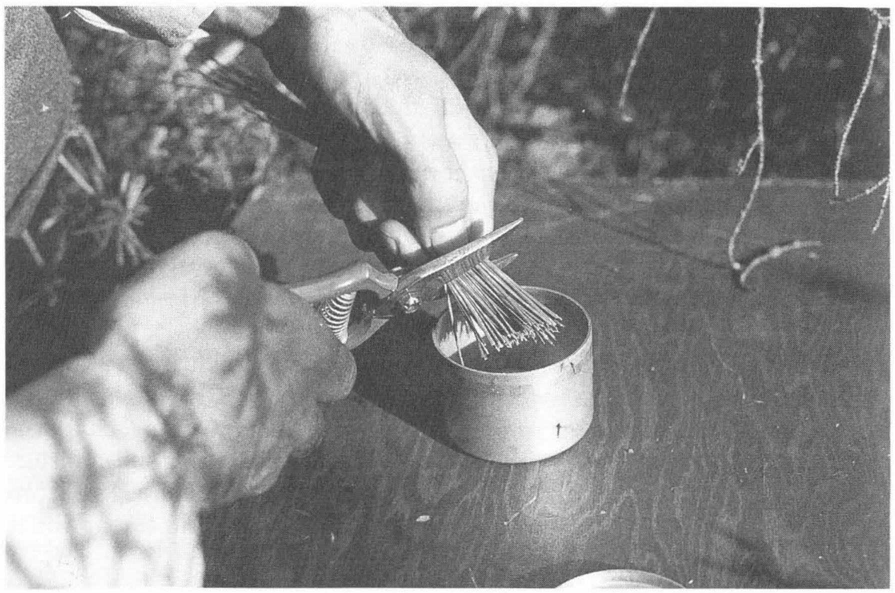


Figure 3.18. *Fuel samples are clipped into a can, weighed, dried, and weighed again to determine moisture content.* Photo by Melanie Miller. From Norum and Miller (1984).

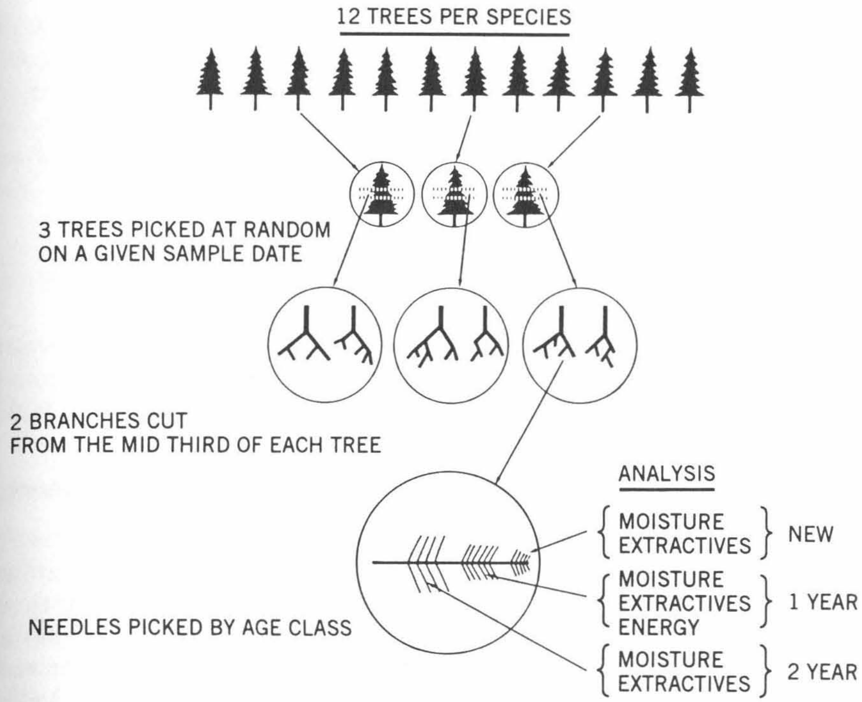


Figure 3.19. *A foliage sampling scheme used for ponderosa pine and Douglas fir.* From Philpot and Mutch (1971).

A method of estimating dead fuel moisture for a site is based on fuel-moisture indicator sticks, consisting of four $\frac{1}{2}$-inch ponderosa pine sapwood dowels spaced $\frac{1}{4}$ inch apart on two $\frac{3}{16}$-inch dowels. The $\frac{1}{2}$-inch dowels are approximately 20 inches long. Each set is carefully adjusted to weigh 100 g when ovendry. The sticks are exposed 10 inches above a litter bed in the open on wire brackets (Figure 3.20). Forest and rangeland fuel, of course, does not consist of dowels. Thus this method is somewhere between direct measurement and inference. The moisture of the stick is determined from its weight and an inference is made about the moisture of the fuels in the area. The value of this method is in its ease of use and consistency. The indicated moisture represents the cumulative effects of past changing weather factors on these standardized fuel sticks over a period of time preceding the observation.

Inference Fuel moisture can be inferred from other information, such as the color of the vegetation. Mutch (1967) related the color of cheatgrass to moisture content. When cheatgrass is dead, it responds readily to changes in atmospheric moisture because of its fine structure. The characteristic color changes while it is curing (from green to purple to straw color) indicate impending flammability because these colors are generally correlated with

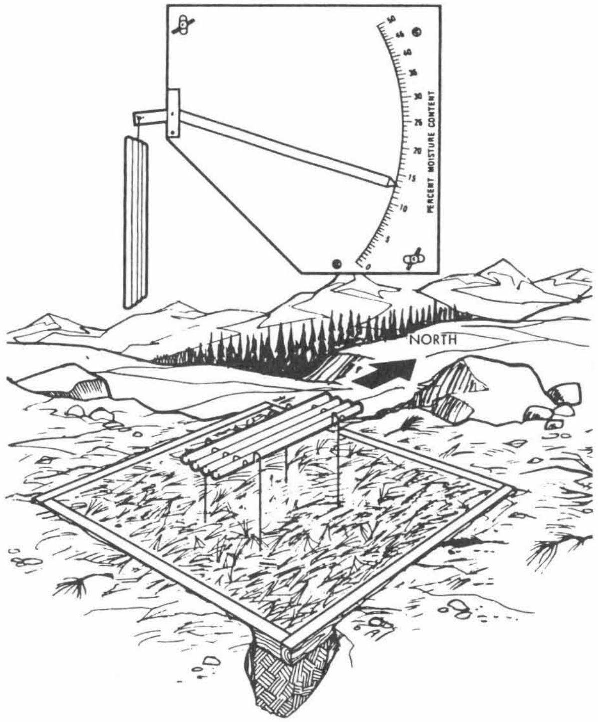


Figure 3.20. *Fuel moisture indicator sticks of the $\frac{1}{2}$-inch size are used to estimate the moisture content of dead fuels of comparable timelag. They are exposed on a wire rack 10 inches above a bed of litter. By weighing them, their moisture content can be obtained.* From Schroeder and Buck (1970).

progressive drying of plants. An experiment at several sites came up with the following relationship: green is >100%, purple is 30–100%, and straw is <30%.

Fuel moisture inference can also be applied at a very different scale. Burgan and Hartford (1993) discuss the use of satellite imagery to assess the state of live vegetation for wildland fire potential in the United States. (Similar methods have been applied elsewhere.) The Normalized Difference Vegetation Index (NDVI) is calculated from reflectance of red and near infrared light from earth's surface. The NDVI value is related to the amount of actively growing biomass, increasing with greenup and decreasing as vegetation cures.

Calculation For some types of fuel, mathematical models have been developed for calculating fuel moisture as a function of observable weather variables. Because the response of dead fuels is physical rather than biological, more work has been put into those models. A fine dead fuel moisture model can be based on recent conditions, while a larger fuel must be calculated from a longer record of weather data. Calculations are especially valuable in using forecasted weather to assess future moisture values, in planning applications, and in comparing one day to the next or one site to another. Models provide consistency. All of the influencing variables are not included in the models, nor will site variability be reflected. Models won't give the moisture for individual fuel particles, but rather a representative value for an area.

3.5 SELECTED EXAMPLES

Following is a discussion of two fuel complexes, palmetto–gallberry in the southeastern United States and aspen in the western United States. Concepts of fuel type, fuel state, and change over time are illustrated.

Palmetto–Gallberry

Palmetto and gallberry are two of the most common plants occurring in forest understories on the Lower Coastal Plain of the southeastern United States. In this area, live and dead fuels accumulate so rapidly that a wildfire in a 5-year accumulation can seriously damage or kill the pine overstory, even though the pines are fire resistant. To preclude destructive wildfires, burning is often prescribed for hazard reduction (Figure 3.21). The fuel type, called palmetto–

Figure 3.21. *The palmetto–gallberry fuel type in the southeastern United States is burned periodically to reduce fire hazard in pine plantations.* Photo from USDA Forest Service.

gallberry, is the complex association of saw palmetto and common gallberry with many other plants beneath slash pines or mixtures of slash and longleaf pine. Openings frequently contain small shrubs and wiregrass.

The mathematical model developed by Rothermel (1972) predicts fire spread and intensity best if the fuel is relatively homogeneous. It is difficult to adequately characterize a heterogeneous fuel complex like the palmetto-gallberry type where fuel height and fuel loading vary widely. Fuel height may range from 1 to 6 or more feet, while loading may vary widely from 1 to 25 tons/acre. This variation makes it impossible to construct a single fuel model that is typical of the type.

Hough and Albini (1978) characterized the palmetto-gallberry fuel complex and then adjusted several variables, such as fuel depth and moisture content of extinction, so that the output of Rothermel's model was representative of measured fire behavior. They developed a dynamic fuel model that accounts for site conditions, fuel-accumulation time, and species composition. The model permits reasonably precise prediction of fire behavior, as well as systematic analysis of the consequences of fuel treatments.

A palmetto-gallberry fuel complex can be completely described by specifying age of rough (years since last burn), height of understory (visual height), percentage of coverage by palmetto, basal area of overstory stand, and moisture content of dead and live fuels. The first three variables define the standing understory fuel loadings by size class. The overstory stand density (basal area) is an indicator of tree biomass and hence of foliar litter production rate. This variable, in conjunction with the age of the rough, permits the computation of litter accumulation (pine needles) on the site. The equations used to estimate fuel loading are given in Figure 3.22. Physical and chemical characteristics of fuel components are given in Figure 3.23.

Fuel component dry weight	Regression equation
Live foliage	$-0.0036 + 0.00253(AR) + 0.00049\ (PPal) + 0.00282(HT^2)$
Live 0–$\frac{1}{4}$ inch	$+0.00546 + 0.00092(AR) + 0.00212(HT^2)$
Live $\frac{1}{4}$–1 inch	$-0.02128 + 0.0014(AR^2) + 0.00314(HT^2)$
Dead foliage	$+0.00221(AR^{0.51263})\exp(0.02482\ (PPal))$
Dead 0–$\frac{1}{4}$ inch	$-0.00121 + 0.00378(\ln AR) + 0.00118(HT^2)$
Dead $\frac{1}{4}$–1 inch	$-0.00775 + 0.0021\ (PPal) + 0.00007(AR^2)$
L layer	$(0.03632 + 0.0005336(BA))\ (1 - (0.25)^{AR})$

Note: AR, age of rough (years); PPal, coverage of area by palmetto (%); HT, height of understory (ft); BA, basal area of overstory (ft^2/acre).

Figure 3.22. *Equations used to estimate fuel loading (lb/ft^2 on dry-weight basis) of palmetto-gallberry fuel components used as input to Rothermel's 1972 fire model.* From Hough and Albini (1978).

Fuel condition and size class	Low heat value (Btu/lb)	Particle density (lb/ft^3)	Total ash (lb/lb)	Silica-free ash (lb/lb)	Surface area/volume (ft^2/ft^3)
Aerial fuels					
Live foliage	8175 ± 92	45.5 ± 3.4	0.041 ± 0.007	0.015 ± 0.007	2322 ± 211
Live 0–$\frac{1}{4}$ inch	8302 ± 66	49.6 ± 1.5	0.032 ± 0.005	0.017 ± 0.006	467 ± 98
Live $\frac{1}{4}$–1 inch	8166 ± 179	47.4 ± 3.2	0.016 ± 0.002	0.012 ± 0.001	166 ± 35
Dead foliage	8299 ± 256	30.7 ± 1.0	0.038 ± 0.001	0.009 ± 0.002	1999 ± 359
Dead 0–$\frac{1}{4}$ inch	8229 ± 184	31.9 ± 2.7	0.031 ± 0.006	0.010 ± 0.006	322 ± 60
Dead $\frac{1}{4}$–1 inch	8167 ± 335	27.4 ± 4.3	0.013 ± 0.002	0.006 ± 0.002	151 ± 37
Surface fuels					
Dead L layer	8592 ± 138	30.4 ± 3.2	0.036 ± 0.016	0.012 ± 0.016	1806 ± 230
Dead 0–$\frac{1}{4}$ inch	8229	31.9	0.031	0.010	325 ± 52
Dead $\frac{1}{4}$–1 inch	8393 ± 119	27.0 ± 4.2	0.018 ± 0.008	0.011 ± 0.004	107 ± 23

Note: Values are means ± standard deviations.

Figure 3.23. *Physical and chemical characteristics averaged over all plots by major fuel conditions and size classes representing the palmetto-gallberry fuel complex.* From Hough and Albini (1978).

Aspen

Aspen is widely distributed throughout North America. It occupies approximately 7 million acres in the western United States. Fire has played an integral part in the development of aspen forests (see Figure 3.2e). Aspen exists as both a climax and seral species but is seral on the majority of sites, eventually to be replaced by conifers. On stable aspen sites, frequent fires can maintain a grass-forb community, with aspen suckers confined to the shrub layer. Infrequent fires produce varying effects on stand structure. Low-intensity fires cause thinning and encourage an all-aged condition. High-intensity fires result in new even-aged stands. Seral aspen is gradually replaced by conifers. This may take 200 to 400 years or more, depending on the potential for establishment and growth of conifers. If succession continues without fire, aspen will eventually be crowded out.

Brown and Simmerman (1986) provide methods for appraising fuels and flammability in aspen forests as a means for choosing good opportunities for prescribed burning and for determining the environmental conditions favorable for a successful burn. Fuels were classified into five types that differed substantially in vegetation and potential fire behavior. The classification of understories was keyed to amount of shrubs and productivity of herbaceous vegetation. Photographs of each plot were rated in terms of potential fire behavior for an "average bad" fire weather situation. Five expressions of fire behavior were rated: rate of spread, fire intensity, torching, resistance to control, and overall fire potential. An example from the photo series is shown in Figure 3.24. Figure 3.25 is a summary of fuel data from the sampled stands. Predicted fireline intensities for typical late summer conditions (Figure 3.26) reflect the differences among fuel types due to fine fuel loadings, particularly the high herbaceous component.

Determining when fuels are ready to burn is more complicated in aspen forests than in most other vegetation types. Curing is probably the most important variable to monitor. Finding the proper time for ignition requires waiting until live fuels are adequately cured and selecting the time when windspeed and dead fuel moistures are in prescription. Adequate curing is particularly important where herbaceous vegetation is the primary fine fuel. Curing increases flammability considerably in these types. The trade-off, however, between waiting for further curing to increase flammability and autumn rains that end the burning season means that aspen stands should be burned as soon as possible. Delays in burning will result in fewer accomplishments because the time in prescription is usually short.

Figure 3.27 shows curing trends and moisture content of live fuels in aspen stands for two seasons. The grasses had substantially lower moisture contents and cured at faster rates during early summer than forbs. Differences in moisture contents of the green and transition stages was relatively small, especially for forbs. Thus moisture contents of the green and transition stages can be considered the same for purposes of estimating curing and judging flammability. The transition stage typically is characterized by yellowing of plant parts.

Fuel class: Aspen/tall forb — Stand No. 21

Community type: *Populus tremuloides/Ligusticum filicinum*

FUEL LOADINGS	*Lb/acre*	*kg/m²*
a. Herbaceous	1,060	0.119
b. Shrub	40	.004
c. Litter	1,130	.127
Downed woody		
d. 0 to ¼	180	.020
e. ¼ to 3	16,030	1.797
f. 3+	59,510	6.670
Subtotals		
Fines	2,400	.270
D. woody 0-3	16,210	1.816

VEGETATION CHARACTERISTICS	
Shrub cover, %	3
Basal area, ft²/acre	
Aspen	203
Conifer	0

FIRE RATING	
Intensity	Low-Med
Rate of spread	Low
Torching	Low
Resistance to control	Medium
Overall	Low-Med
Probability of a successful burn	Moderate

STAND LOCATION	
National Forest	Bridger-Teton
Ranger District	Jackson
Drainage	Little Dry Cottonwood Creek
Photo date	September 1983

Figure 3.24. *Example from the photo series for aspen fuels.* From Brown and Simmerman (1986).

Fuel	Aspen/ shrub	Aspen/ tall forb	Aspen/ low forb	Mixed/ shrub	Mixed/ forb
			Lb/acre		
Herbaceous	670 (230 to 1,000)	1,330 (1,030 to 2,020)	300 (180 to 460)	90 (80 to 90)	290 (10 to 550)
Shrubs[1]	3,170 (980 to 6,150)	110 (0 to 440)	260 (0 to 630)	3,040 (2,480 to 3,610)	630 (100 to 1,350)
Litter	1,810 (420 to 2,810)	1,600 (790 to 2,240)	1,350 (170 to 2,740)	1,980 (1,920 to 2,040)	1,680 (740 to 2,560)
Fines[2]	6,140 (4,030 to 9,390)	3,170 (1,970 to 3,990)	2,430 (1,640 to 3,330)	6,050 (5,850 to 6,250)	3,070 (2,150 to 3,560)
Downed woody 0 to 1 inch	2,440 (710 to 4,220)	1,080 (620 to 1,440)	2,600 (1,460 to 3,690)	4,240 (3,400 to 5,080)	2,710 (1,440 to 3,900)
Downed woody 0 to 3 inch	7,020 (3,580 to 12,510)	7,340 (1,510 to 16,210)	5,720 (3,290 to 7,600)	6,970 (5,550 to 8,390)	7,810 (4,090 to 12,250)
			Percent		
Shrub cover	40 (30 - 60)	10 (0 - 20)	10 (0 - 30)	60 (60 - 70)	20 (10 - 30)

[1]Shrubs include foliage and stemwood.
[2]Fines include live and dead herbaceous plants and shrubs, litter, and 0- to ¼-inch downed woody fuel.

Figure 3.25. *Average fuel loadings and shrub cover from sampled stands representing the aspen fuel types. Ranges in values are in parentheses.* From Brown and Simmerman (1986).

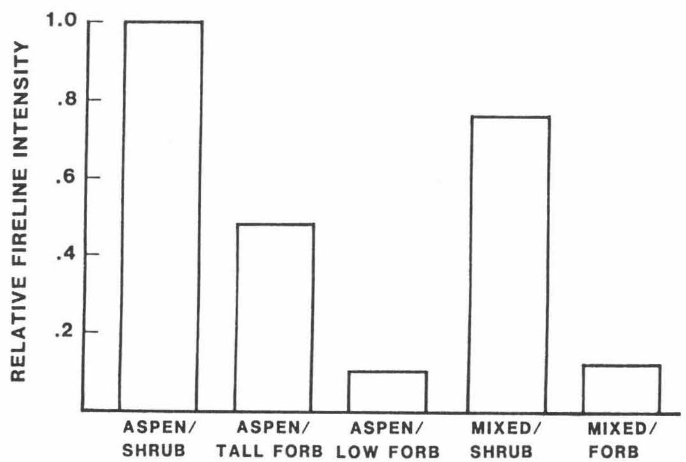


Figure 3.26. *Fireline intensity calculated under the assumption that 50% of the herbaceous vegetation is cured, fine fuel moisture content is 8%, slope is 0%, and midflame windspeed is 4 mi/h. The intensities are relative, being expressed as a fraction of the intensity for aspen/ shrub.* From Brown and Simmerman (1986).

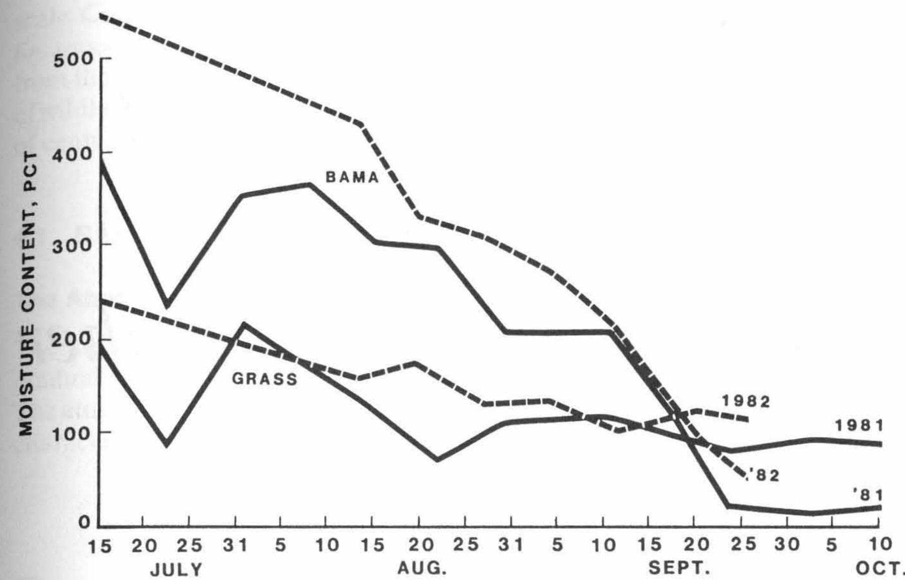


Figure 3.27. *Moisture content of herbaceous vegetation from an aspen stand in Wyoming. Precipitation during August and September was 1.56 inches in 1981 and 4.66 inches in 1982.* From Brown and Simmerman (1986).

Cured leaf tissue shows brown coloration rather than yellow. Cured grass stocks remain straw colored, but the yellow is largely washed out.

Under aspen canopies, frost damage occurs later than in open areas or than in low-lying areas where cold air collects. A hard freeze, however, can cure live vegetation quickly. Temperatures less than 15 to 20°F can cure forbs and shrub foliage in just a few days. If the freeze occurs before abscission layers form, the shrub leaves will remain attached to the stems, adding to the flammability of surface fuels.

FURTHER READING

Fuel models for the U.S. Fire Behavior Prediction System are described by Anderson (1982) in "Aids to Determining Fuel Models for Estimating Fire Behavior," by Burgan and Rothermel (1984) in "BEHAVE: Fire Behavior Prediction and Fuel Modeling System—FUEL Subsystem" and by Burgan (1987) in "Concepts and Interpreted Examples in Advanced Fuel Modeling."

Canadian fuel types are described by the Forestry Canada Fire Danger Group (1992) "Development and Structure of the Canadian Forest Fire Behavior Prediction System." Canadian fuel types are also illustrated in posters such as Alexander and Lanoville's (1989) "Predicting Fire Behavior in the Black Spruce-Lichen Woodland Fuel Type."

Schroeder and Buck (1970) include a good chapter on fuel moisture in their book *Fire Weather.*