Chapter 5
Fuel Moisture

Water is the driving force of all nature
Leonardo da Vinci

5.1 Background

Moisture content is the most dynamic feature of most wildland fuel types and it influences nearly all fire processes, especially ignition, combustion, and smoldering. The amount of moisture in the fuel is called the fuel moisture content (FMC) defined as the mass of water per unit mass of dry material and is often expressed as a percent. FMC is a major factor determining the heat produced by a wildland fire (see Table 2.2). High fuel moistures slow the rate of burning and fuel consumption in a number of ways. Heat from the fire must first volatilize the water bound in the fuel by boiling it off as gas before it can ignite the organic fuel (Simard 1968). This steals heat away from ignition and combustion processes, and if there is not enough heat to drive off a sufficient amount of moisture, then ignition will not occur. High moisture values may also cause increased particle thermal conductivity (how fast heat can pass through an object) and volumetric heat capacity (heat output per unit volume of fuel) that may further dampen ignition and combustion (Nelson 2001). Fuel moisture also reduces flame temperature thereby increasing smoldering combustion and the production of char while retarding the rate of consumption. Because moisture reduces both ignition potential and combustion temperatures, there is a corresponding increase in the time it takes a fuel particle to burn (residence time). Water vapor created from the heat of combustion may surround the fuel particle and dilute the available oxygen thereby also retarding combustion (Simard 1968). These complex interactions contribute to a lack of ignition, or if ignited, to lower heat emissions and longer burning times. This, in turn, can result in less flaming combustion, decreased fuel consumption, and increased smoldering. This is why every fire behavior model has fuel component FMCs as input parameters (Matthews 2013).

Three significant fuel characteristics affect moisture of live and dead fuel particles (Nelson 2001). The chemical composition of the fuel dictates its ability to attract and hold water molecules from the surrounding environment; a fuel property

called *hydroscopy*. In general, wood is mostly composed of cellulose (~50%), hemicellulose (~20%), and lignin (~20%); needles have less lignin and more cellulose (Chap. 2). First, cellulose has a greater ability to hold water than lignin because of its chemical structure (i.e., more hydroscopic). The ability of the fuel particle to hold water dictates the rate of moisture loss. Second, the internal cell structure of the fuel strongly influences moisture dynamics and it differs for live and dead fuels. Cell walls of most dead fuels are hygroscopic. Water molecules that are attracted to and eventually adhere to cell walls become bound water and have low vapor pressure (Schroeder and Buck 1970). Free water consists of those water molecules that are not bound to the chemical structure of the fuel. Third, the physical properties of the fuel ultimately control moisture retention. These include all of those properties described in Chap. 2, but especially particle density, size, and shape. Dense, large, round coarse fuels dry slower than less dense, small fuels that have high surface areas.

Live fuels have completely different moisture dynamics than dead fuels. In short, live fuel moistures are dictated by the ecophysiological processes of transpiration and soil water dynamics, while dead fuel moistures are driven by the physical process of evaporation. Both live and dead fuel moisture dynamics are driven by the gradient of vapor pressure (humidity) from the particle to the atmosphere; water molecules tend to migrate to drier conditions. Dead and live FMCs also have a complex spatial distribution because the biophysical factors that control FMC dynamics vary widely across space as they interact with plants, necromass, weather, and topography.

Although this chapter discusses fuel moisture in the context of how it is used to predict fire behavior and effects, live and dead fuel moisture dynamics interact with many other ecological and physical processes. Moist fuels, for example, decompose more rapidly and are more susceptible to fragmentation than dry fuels. Dry fuels intercept more precipitation and reduce water availability for plant growth. The primary objective of this chapter is to familiarize the reader with the biophysical processes that control fuel moisture, how they relate to wildland fuel dynamics (Chap. 6), and how to measure or estimate fuel moistures. A more comprehensive discussion of live and dead fuel moisture dynamics for fire managers is provided in Schroeder and Buck (1970) and a more scientific treatment is provided by Nelson (2001).

5.2   Dead Fuel Moisture Dynamics

Water moves through dead wood fuel particles via three mechanisms—capillarity forces, infiltration, and diffusion. *Capillary forces* draw water through fuel particles via fine capillaries in cell walls and cell structure. *Infiltration* involves the flow of free water through a fuel particle via gravitational forces. The primary mechanism is *diffusion* in which water in gaseous form (vapor) diffuses into and through a fuel particle driven by a moisture gradient; water vapor is drawn from areas of

high moisture to areas of lower moisture to achieve equilibrium. Water vapor can either condense on cell walls or continue to diffuse through cell voids to any area of lower moisture. The steeper the particle water vapor gradient, the faster the diffusion process. Diffusion is governed by cell structure (i.e., pore space, cell wall composition), which varies by plant life-form and species of the dead particle, and particle age (stage of decomposition). In summary, water and water vapor move through a fuel particle in a progression of processes consisting of evaporation of water from cell walls, diffusion of the water vapor across cell voids and through cell walls, condensation on another cell wall, and bound water transport across a cell wall, all aided by capillary forces and infiltration. Eventually, water is evaporated from the particle surface into the atmosphere and lost from the fuel particle.

Two physical properties of the fuel represent these processes in modeling dead fuel moisture dynamics within a particle. Particle *permeability* is the ability of water to flow through cell cavities or how fast water can be transported across the particle. Cell structure, chemical composition, size, shape, and degree of decomposition all play a role in influencing the permeability of water through a dead fuel particle. Moisture *diffusivity* is the potential for the flow of water molecules across cell walls and is mostly governed by the degree of hygroscopy of the cell walls within the dead fuel particle.

To simplify complex physical FMC processes, dead fuel moisture dynamics is mostly governed by the water vapor pressure difference (dry to wet) between the atmosphere and the fuel particle. This difference is primarily driven by temperature, relative humidity, and the presence of water on the particle surface (Matthews 2013). If the atmosphere–particle vapor pressure difference is positive, such as when the temperature is high, relative humidity is low, and fuel is wet, then water is lost from the particle into the atmosphere through a process known as *desorption*. The free water in the intercellular space is easily evaporated to the atmosphere, but the vapor pressure deficit (difference in humidity of cell spaces and the air) must be great to drive bound water from the cell walls. *Adsorption* occurs when atmospheric humidity increases and dry fuel particles gain moisture as water molecules adhere to the particle surface resulting in increasing FMC (Simard 1968). The processes of desorption and adsorption introduce an important aspect of dead FMC dynamics—the FMC for any dead fuel particle is greatly dependent on its past conditions. This is called fuel moisture *hysteresis* in which today's fuel particle's FMC is dependent on past FMCs. As a result, most empirical equations that simulate fuel moisture include the previous days' FMC values (Viney 1991).

If there is rain, then free water on the particle surface can be *absorbed* by the particle until either the fuel particle has reached the fiber saturation point (fully saturated with water) or the precipitation stops and free water on the particle surface evaporates. Water absorption into fuel particles is a slow process, especially for large woody fuels, that depends on the many factors including initial moisture content, particle condition (percent rot, amount fragmentation), and type of particle (wood, grass, needle litter). As a result, the amount of rainfall may be unimportant because, during heavy rainfall events, most of the precipitation may run off or evaporate from the particle before being absorbed. Therefore, the duration of

Fig. 5.1 Drying curve of a
5 cm-deep litter layer under
temperature and humidity
conditions for which the
equilibrium moisture content
(EMC) is 5.5 %. (Schroeder
and Buck 1970)
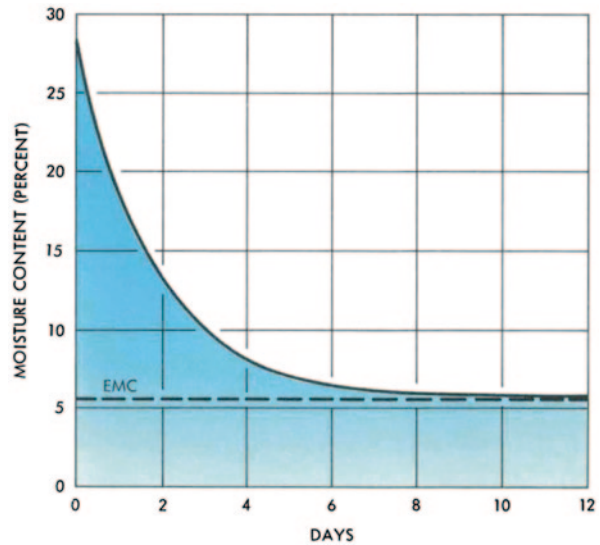
rainfall, not the amount, is often used in fuel moisture modeling (Viney 1991). Dew
can also condense on a fuel particle provided that the particle's temperature is at
dew point and this condensed free water can be directly absorbed by the particle.
Moisture from the ground can also be conducted to a fuel particle if the ground is
wet, and water evaporated from the ground surface can condense on the cooler fuel
particle (Pyne et al. 1996).

Any discussion of dead FMC dynamics requires the introduction of another term
to illustrate how fuel dries over time. The equilibrium moisture content (EMC) is
the final FMC of a dead fuel particle when it is exposed to constant temperature
and humidity conditions for a period of time. When the difference in vapor pres-
sure between air and the fuel particle is zero, the moisture of a dead fuel particle
is in equilibrium with the constant environment (Fig. 5.1). EMC curves differ for
each type and size of particle as well as for each set of temperature and humidity
conditions. Most fuel particles rarely reach EMC because the surrounding environ-
ment changes rapidly and desorption rates are slow. The process of adsorption and
desorption can also be illustrated using the relationship of EMC to relative humidity
(Fig. 5.2). Low humidities allow desorption to decrease EMCs resulting in drying
fuels (lower FMCs), while higher humidities increase adsorption to increase EMCs
and ultimately FMCs. One application of EMC is in the construction of drying
curves (Fig. 5.2) that show how the relative humidity affects the EMC at a constant
temperature, in this case, of 27 °C (80 °F) of a fuel particle (needle) during both the
adsorption (when the air is moister than the particle) and desorption processes.

Fire scientists have condensed the complex process of dead woody fuel moisture
dynamics into the time-lag concept discussed briefly in Chap. 3. A *time lag* is the
time it takes for a fuel particle to lose 63 % of the difference between its initial mois-
ture content and its EMC under constant conditions (80 °F, 20 % relative humidity)

Fig. 5.2 The equilibrium
moisture content (EMC)
of sugar maple wood at a
constant temperature of 27 °C
(80 °F), but different levels of
humidity when the humid-
ity in the air is greater than
in the dead fuel (adsorption)
and when the air is drier than
the fuel (desorption; Djolani
1970)
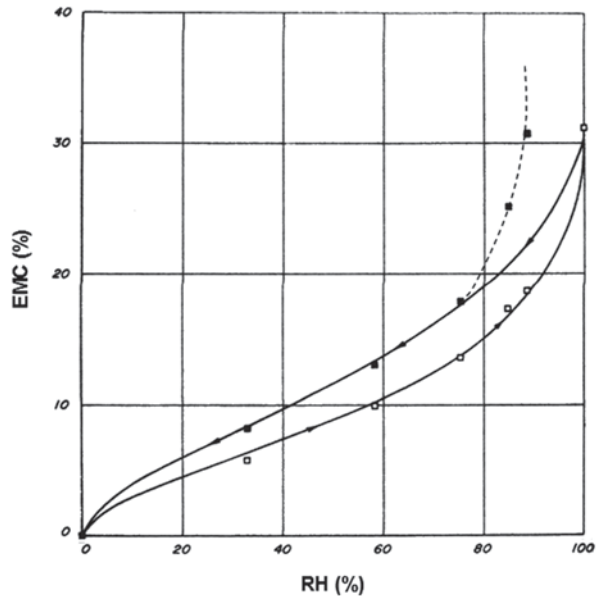
assuming an exponential drying function. One hour (1-h) woody fuel particles, for
example, lose approximately two thirds of their moisture in 60 min. It takes about
four time lags to get to 95 % of the EMC, historically set at 4.5 % (Fosberg et al.
1970). Time lags increase logarithmically with the diameter of the woody fuel par-
ticle; 10-inch diameter particles take 10 times longer to dry (100 days) than 1-inch
particles (1 day; Fig. 5.3). Larger particles take longer to dry because diffusion
has to pull water vapor from the wetter areas inside the wood to the drier, outside
areas of the wood particle, which can only happen when the air is quite dry. As a
result, the inside wood of larger particles (1000 h fuels) will often be wetter than
the outside wood.

   Fuel moisture dynamics are quite different for duff and litter as compared to
wood. Time lags for litter and duff are highly variable and depend on depth, type,
stage of decomposition, and a host of other biophysical factors. A 2 -inch-deep litter
layer in a ponderosa pine stand, for example, might have a time lag of 48 h or the
equivalent of a 1.4 in diameter woody fuel (Schroeder and Buck). Hydraulic proper-
ties of duff and litter mostly depend on the degree of decomposition with slightly
decomposed material having large pore spaces resulting in increased hydraulic con-
ductivity and faster drying and wetting (Plamondon et al. 1972). As decomposition
proceeds, the size of the organic particles decreases resulting in smaller pores with
higher moisture retention properties and slower drying. Hydraulic conductivity de-
creases significantly with the degree of decomposition. Duff bulk density is a useful
indicator of pore size distribution and hence, can represent hydraulic conductivity
and moisture retention in organic soils. Duff layers with high bulk densities, for
example, may take longer to dry.

Fig. 5.3 The timelags of different diameter woody fuel particles. (Schroeder and Buck 1970)
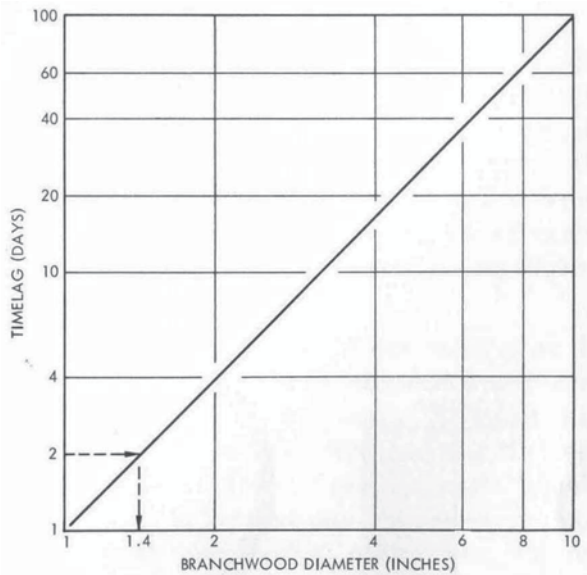
5.3   Live Fuel Moisture Dynamics

Unlike dead fuel moisture, live fuel moistures are dictated by the responses of living plants to their surrounding environment (Pyne et al. 1996). Plants grow by transforming water, carbon dioxide, and the sun's energy into biomass via photosynthesis (Eq. 2.1) and they maintain this living biomass through the process of respiration, which also uses water. Plants get the water needed for respiration and photosynthesis from the soil though a series of complex processes known as water transport. When the ambient air is dry, there is a difference in vapor pressure (amount of water in the air) from the atmosphere to the stomatal cavities in the plants, photosynthetically active biomass (foliage). This difference creates a moisture gradient that pulls water from the foliar cells into the cell void and then through the stomata and into the atmosphere via a process known as transpiration (Campbell 1977). The movement of water out of the cell walls and into the intercellular spaces sets up a diffusion gradient and provides the tensional pressure to pull water through living cells from the roots, through the xylem, to the foliage, and out to the atmosphere.

   Three factors control water transport in plants and therefore live fuel moisture dynamics: (1) osmotic forces caused by diffusion of water across the plant's cellular membranes, (2) capillary tension forces, and (3) diffusion across cell voids. Water enters the roots through diffusion when the transpirational pull, often called plant water potential, is greater than the soil water potential (forces that bind water to soil particles). Water moves through cells via osmosis and through cell voids by diffusion and capillary forces. The diffused water is then pulled up to the foliage through xylem conductive tissue in the wood by tensional pressure caused by plant water potential that is driven by the vapor pressure gradient from the air to the plant. As

the soil water becomes depleted, the diffusional gradient must become greater to exert more tensional pressure to overcome the tensional forces that the soil exerts on the bound water. The moisture content of live fuels comes from the free and bound water and water vapor in plant's cellular void spaces, cell walls, and conducting tissue. This water is under tension due to transpirational pull and other forces such as capillary and surface tension. If soil water is abundant, plants open their stomata thereby initiating the vapor pressure gradient to pull soil water through cells for use in photosynthesis and respiration. However, there always needs to be some water within the plant to maintain respiration and keep the plant living, so live FMCs rarely get as low as dead FMCs. Most plants in fire environments have the ability to shut their stomata to control water loss that ensures the plant stays alive thereby keeping live FMCs high (Waring and Running 1998).

Many exogenous environmental factors control water transport in plants. As mentioned, humidity of the atmosphere is the primary engine that draws water from the soil and dictates the rates of transpiration (Campbell 1977). Soil properties, such as depth and percent rock, sand, silt, and clay will dictate soil water-holding capacity, permeability, and flow rates that then control the amount of free and bound water available for the plant throughout the year (Eagleson 1978). Precipitation is of critical importance in keeping the soil plenum full. Enough water has to fall so that it is not evaporated, intercepted by the live foliage, or absorbed by the ground fuels so that it can eventually seep into the soil and be available for plants. Increases in solar radiation may increase photosynthesis resulting in greater water usage and earlier water deficits contributing to lower FMCs. Topography is also important in that it will influence subsurface water flows to and away from the soil plenum, and it controls radiation, snowfall, and drainage dynamics.

While live fuel moisture dynamics are more complex than dead fuel moisture, live fuel moistures are also more stable over longer time periods. In general, live fuels, especially new plant growth, have the highest fuel moistures during the growing season when water is abundant and the new cells consist mostly of water with little structural material (Fig. 5.4). As cell walls harden and cell growth consists mostly of structural tissue, the mass of organic matter increases and the mass of water remains stable. As a result, the ratio of dry matter to water increases thereby lowering relative moisture content but not plant moisture. This is why moisture contents of older foliage are rarely as high as new foliage (Fig. 5.4). As soil water becomes scarce, water in the cells and cell voids becomes depleted causing major to minor decreases in live FMCs depending on the plant species. However, live foliar moisture rarely goes below the level at which plant cells would die from lack of moisture. Chrosciewicz (1986) found that moisture contents of jack pine and black spruce were approximately 120–130 % in the spring and fall, but dropped to 90 % in the summer. Live FMCs of actively growing foliage and branchwood can be as high as 300 % during the growing season when water is plentiful (Pyne et al. 1996). Conifers and many temperate shrubs may have live FMCs that reach a minimum of 90–100 % during the driest parts of the year. Some xeric shrubs, such as sagebrush, can have FMCs that are as low as 30–50 % during the dry season. The spatial pattern of live FMCs across an area
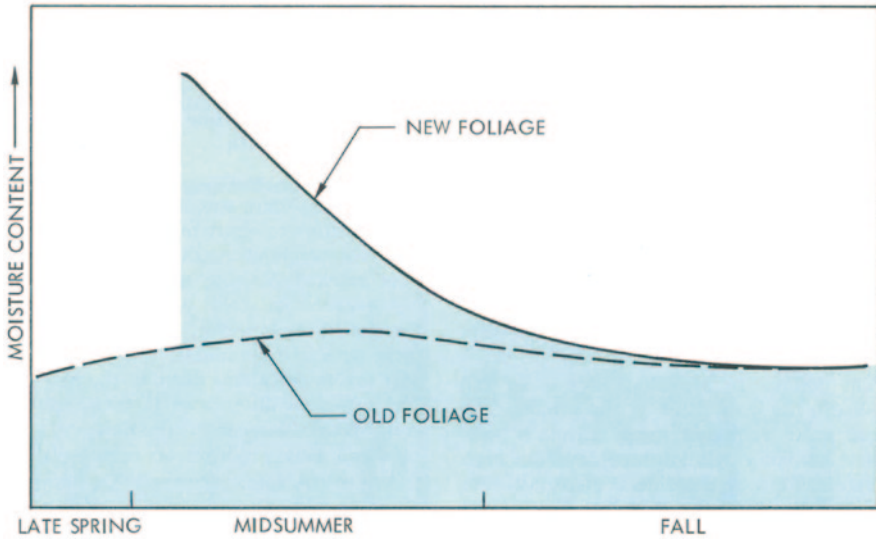
Fig. 5.4 The live fuel moisture content (FMC) of new and old pine needle foliage at different times of the year. Old foliage moisture content does not change throughout the year. (Schroeder and Buck 1970)

can be quite heterogeneous because most forest and range communities consist of a wide diversity of species in different stages of development and phenology (curing), each having different FMC dynamics.

Plant ecology is just as important as the environment when understanding live fuel moisture dynamics. Phenology is important because seasonal changes in plant development influence live FMC throughout the year. Live plant FMCs in the growing season, for example, are always much higher than FMCs of plants in the dormant season. Foliae age in conifers is also important; older needles have thicker, hardened cell walls (Fig. 5.4). There are also great differences among species in their ability to sustain foliage under low moisture conditions. Conifers, for example, have higher minimum foliar FMC values (>90% FMC) in the fire season than xeric shrub species (>30% FMC; Kauffman and Martin 1985). And FMCs can be quite different in a single plant; FMCs are typically higher in the upper third of a conifer's crown than the lower third, which is probably because of the abundance of new needles in the crown top (Brown 1978). Many perennial plants, such as grasses and forbs, allow their foliage to die when FMCs get too low through curing, while other species simply close their stomata to reduce transpiration and limiting water loss thereby maintaining FMC values.

The influence of live fuel FMC on combustion processes is still not well understood (Jolly 2007). Why do dead fuels cease burning when FMCs are above 30%, while tree crowns burn when their moisture content is above 100%? Several factors may contribute to this dilemma. First, water in live fuels is under tension thereby having a higher pressure and lower boiling point. Second, the chemical composition of live fuels is different than dead fuels and the many dissolved compounds

in the bound and free water of live fuels may influence ignition (Jolly et al. 2012; McAllister et al. 2012). Bulk densities and packing ratios of canopy live fuels may facilitate rapid ignition processes to generate great heat outputs that overwhelm moisture effects. Hopefully, future research will provide answers to these important live fuel moisture questions.

5.4   Moisture of Extinction (M_x)

The moisture of extinction (M_x) is the dead or live fuel moisture at which combustion cannot continue (Chap. 2, 3). Trabaud (1976) defined M_x as the maximum FMC above which a fire cannot be sustained and found 45% as threshold value; combustion did not occur above that value or it was delayed more than 15 min. In general, studies have found that fire spread usually stops when dead fuels have an FMC greater than 30%, yet live fuels with FMCs above 100% can support a spreading fire (Scott et al. 2014). Rothermel (1972) first formulated the effect of moisture content on the burning rate by defining a threshold M_x above which fire cannot be sustained. The concept of extinction moisture is difficult to define in field and laboratory experiments because it varies by diverse fuel (size, shape, density) and environmental (temperature, humidity, wind) factors. As mentioned, FMC increases specific heat and thermal conductivity of fuel so that more heat is absorbed by the fuel particles surface layer to drive out moisture, delaying preheating and ignition of fuel until it reaches ignition temperature. If there is too much water, ignition will not occur. The most comprehensive M_x model was provided by Wilson (1985) based on laboratory data using milled wood sticks and shaved excelsior. Ideally, M_x should be an emergent property of fire models that simulate combustion using mechanistic physical process; simulated combustion should cease when moistures are too great. However, most fire models do not have the resolution and detail to accurately simulate the extinction of combustion due to high moistures. Instead, MEs are considered static parameters in combustion models and are assigned as properties of a fuel or particle (Chap. 2). Rothermel (1972), for example, used the ratio of FMC to M_x to calculate a dampening coefficient that reduced fire intensity (Table 2.2).

5.5   Measuring Moisture Content

The most common method of measuring FMC is called gravimetric sampling where fuel is dried in an oven. Fuel moisture is calculated from the difference in fuel weight before and after drying. In general, this method involves collecting fuels in the field and weighing them as soon as possible or placing them in a waterproof container and storing the container in a cold or cool place for transport to the laboratory. Once in the laboratory, fuels are first weighed and then dried in an oven set at temperatures that range from 50 to 105 °C until their weight is stable, typically

requiring times that range from overnight to days depending on the fuel component. The dried fuel is then weighed and the difference between field-measured fuel weight and oven-dried weight is the mass of water lost in the drying process. This water loss is usually divided by the oven-dried fuel mass to get FMC in units of percent (Matthews 2013). The best results for this method occur when samples are dried at lower temperatures (80–85 °C) for longer time periods (48–72 h), which prevent unwanted changes to the organic structure of the fuel particle, especially live fuels and litter.

There are some problems with using the oven-dry method for estimating FMC (Simard 1968). First, fuel samples take a long time to process, making this method difficult to apply in real-time fire management operations, such as prescribed fires and wildfire suppression, when FMCs need to be quickly estimated. Second, care must be taken in both the field and the laboratory to ensure accurate fuel moisture measurements; collected samples must be immediately put into a plastic bag and put in a cool environment to prevent adsorption and water loss before weighing in the laboratory. Drying organic materials in a hot oven may also volatilize other chemical constituents of the fuel particles, especially live foliage, resulting in an unwanted loss of organic biomass and a slight overestimate of FMC. On the other hand, if the oven temperature is too low, some water may be retained in the cell structure and FMC estimates may be underestimated. Some woody fuel particles are so large that it may take days to completely dry the particles, while small fuels, such as twigs, take only hours to dry. These disparate drying times make obtaining a comprehensive set of FMCs for all fuel components difficult in an operational setting.

Several other field methods have been used to estimate FMCs in the field. Banks and Frayer (1966) correlated the angle at which a pinaster pine needle broke to the needle's FMC to create the "leaf-bending method" for quick and easy field use, albeit only for that forest type and only for needles. The "speedy moisture meter" used by Dexter and Williams (1976) measures the pressure of acetylene gas evolved from mixing finely divided fuels with calcium carbide to estimate FMC, but its use was limited because it required careful preparation of fuel particles (Marsden-Smedley and Catchpole 2001). Another FMC method is to pulse an electric charge through the fuel particle and measure electrical signals, such as resistance, impedance, or capacitance. FMC is then calculated from a calibration curve that relates the electric signal to FMC (Stamm 1927). The Wiltronics TH Fine Fuel Moisture Meter, for example, estimates FMC from the electrical resistance of a fine fuel sample (Chatto and Tolhurst 1997). Gravimetric sampling, however, is still the most common and reliable method to calculate FMC (Viney 1991; Chatto and Tolhurst 1997).

Because FMC is difficult to conveniently and accurately measure in the field, it is often estimated using indirect techniques. One indirect method is to estimate FMC for dead woody fuels using fuel analogues or moisture indicator sticks. A set of four wooden dowels of standard size and weight are placed at a weather station and weighed at various time intervals to approximate fuel moisture for 10-h woody fuel component. The current and past moistures of these dowels are related

empirically to estimate FMCs for other fuel components (Schroeder and Buck 1970). Simulation modeling also provides an indirect way to estimate FMCs where computer programs are used to simulate fuel moisture dynamics from weather and fuel inputs (Nelson 2001). In fact, many fire managers use simulated FMCs from the National Fire Danger Rating System (NFDRS) models to estimate local FMCs for their fuels although the simulation of dead fuel FMCs is much better than live fuel FMCs (Anderson 1976). And, in recent years, several studies have found useful empirical relations between FMC and satellite-derived variables in several ecosystems (Paltridge and Mitchell 1990; Chladil and Nunez 1995; Chuvieco and Martin 1994). Dead fuel FMC estimation from remotely sensed data is complex for two reasons: (1) dead fuels are under the vegetation canopy and, therefore, cannot be directly sensed remotely, and (2) dead fuels do not show changes in green coloration from water variations and, consequently, are less sensitive to changes in reflectance. For this reason, FMCs for grasslands was more effectively estimated with higher precision than other fuels because FMC variations in grasslands have a greater influence on those variables that affect plant reflectance (such as chlorophyll content or leaf area index; Paltridge and Mitchell 1990; Hardy et al. 1999).

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