Chapter 2
Fundamentals

Fire's the sun, unwindin' itself out o' the wood
David Mitchell, author

2.1 Fire and Fuel Basics

2.1.1 Fuel Chemistry

Wildland fuels are mostly created from plants, sunlight, water, and nutrients to be eventually burned by fire. Fuels are created by plants as a product of photosynthesis, a chemical process where carbon dioxide (CO_2), water (H_2O), and energy from the sun (solar radiation) are used to produce organic compounds of the chemical form $(C_6H_{10}O_5)_y$ and also oxygen (O_2). This can be expressed in the general formula:

$$5H_2O + 6CO_2 + \text{Solar Energy} \rightarrow (C_6H_{10}O_5)_y + 6O_2. \qquad (2.1)$$

The substances that compose biomass $(C_6H_{10}O_5)_y$ are quite susceptible to burn because of their organic chemical constituency. The primary substances found in plant biomass are cellulose, hemicellulose, and lignin. In general, wood, an important fuel in forest ecosystems, is composed of around 40–55 % cellulose, 15–25 % hemicellulose, 15–30 % lignin, and 2–15 % other matter, while needles have less lignin but more cellulose than wood.

Gisborne (1947) said "all fuels have pretty much the same chemical constituents (cellulose, starch, and lignin) and when these organic fuels burn in a wildland fire, they combine with oxygen to create carbon dioxide, water, and heat" as denoted in the following formula:

$$(C_6H_{10}O_5)_y + 6O_2 \text{ heat} \rightarrow 5H_2O + 6CO_2 + \text{Heat} + \text{secondary compounds} \qquad (2.2)$$

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This is a chemical representation of the process of combustion, often considered a chemical chain reaction because the heat produced by *combustion* acts as a catalyst which further increases the rate of reaction. Byram (1959) presented the following chemically balanced oxidation reaction for complete combustion of plant biomass:

$$\begin{aligned}&4(C_6H_9O_4)+25O_2+[0.322M\ H_2O+94N_2]\rightarrow 18H_2O+24CO_2\\&+[0.322M\ H_2O+94N_2]+[11.6\times 10^9\ \text{J Heat}]\end{aligned} \tag{2.3}$$

Note that 4 kg moles of plant material ($C_6H_9O_4$) yields about 11.6 billion joules of heat, and dividing this heat by the mass gives the heat content of the fuel (see Sect. 2.3.1.1).

2.1.2 Scales of Combustion

The physical process of combustion is quite complex and occurs in at least four overlapping phases (Zhou and Mahalingam 2001; Bebi et al. 2003). In the *pre-ignition phase,* unburned fuel ahead of the advancing flame front is heated and raised to its ignition temperature in a series of endothermic (requiring heat) reactions dominated by dehydration and the volatilization of organics. Water is vaporized in the cell structure, then driven to the surface of the fuels, and vented to the atmosphere. The second phase of combustion known as *pyrolysis* begins as fuel temperature rises and cellulose and other compounds begin to decompose to release combustible organic gases and vapors, thereby converting biomass into volatiles, tars, char, and ash. Cellulose is pyrolyzed between 280 and 400 °C through dehydration and depolymerization, while lignin is pyrolyzed at temperatures of 280–500 °C because it is more complex and thermally stable (Liodakis et al. 2002). The *combustion phase* occurs when the burning process becomes exothermic (generating heat) in the presence of oxygen giving off energy in the form of heat and light, and the start of combustion is often termed ignition. Flaming combustion occurs when volatized gases are oxidized and flames are generated, usually occurring when the temperature of the volatiles reach 450–500 °C. Combustion without flames is called smoldering combustion, which is the surface oxidation of char, which provides just enough heat to continue pyrolysis. In general, the *smoldering combustion phase* occurs when the concentration of combustible vapors above the fuel is too small to support a persistent flame, so gases and vapors condense, appearing as smoke. Once most volatile gases have been driven off, the *glowing combustion phase* occurs, where only embers and smoke are visible and there is little smoke; the carbon remaining in the fuel is oxidized to continue to produce significant heat.

This complex combustion process is often simplified so that it can be taught to fire specialists using the famous "fire triangle" (Fig. 2.1). At the finest spatial scale, a combination of three elements is needed for a wildland fire to burn: heat, oxygen, and fuel (Countryman 1969). The heat source for ignition can be from lightning, matches, drip torches, or, mostly, the fire itself. Oxygen is in great supply in the earth's atmosphere, but sometimes the combustion process itself may use

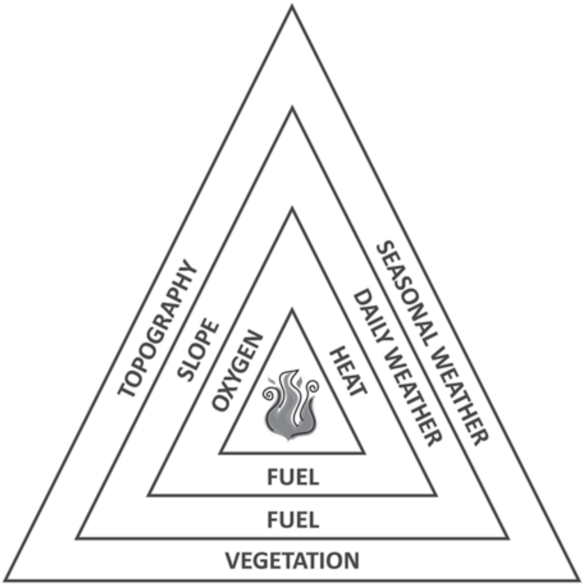

Fig. 2.1 A new variation on the traditional fire triangle often used to teach fire science to managers. The *inner triangle* refers to combustion at the flame level, the *middle triangle* refers to fire spread at a stand level, and the *outside triangle* refers to fire growth at the landscape level

more oxygen than can be supplied by the atmosphere, thereby governing burning rates. And last, there is fuel. As Van Wagner (1983) mentions, the fuel must be the appropriate size and arrangement to facilitate fire spread and it must be dry enough for combustion (i.e., low moisture content). Unfortunately, the inner fire triangle in Fig. 2.1 really only works at very small scales; perhaps the scale of the flame, which may be useful for firefighters but somewhat ineffectual for the diverse and complex issues facing a wildland fuel manager. Therefore, many have added additional fire triangles to represent the scaling of combustion to a fire event (Fig. 2.1; Alexander 2014).

However, to fully understand fuels, it is important to recognize that the process of combustion scales from the flame to burning period to fire event over various time and space scales (Fig. 2.1). A more comprehensive representation of the fire triangle is detailed by Moritz et al. (2005; Fig. 2.2) where fire moves across an area and interacts with topography (slope, aspect), weather (temperature, humidity), and the fuel complex. At coarser scales, the fuel properties important to fire spread are governed more by the distribution of fuels across the landscape or contagion (continuity of a fuelbed). The landscape-level spatial scale of fire spread best describes the operational management of fuels and is probably the most appropriate for designing fuel treatments (Agee and Skinner 2005). However, some large fires can burn entire landscapes over the course of weeks, and as more fires burn the same landscape over hundreds of years, these fires interact with previous fires, climate (drought, warming), ignition patterns (lightning, humans), and vegetation to create a *fire regime* (Chap. 6). In Fig. 2.2, fuels are represented by vegetation to signify that fuel conditions change over time and this change is mediated by vegetation development processes (regeneration, growth, mortality) and succession (species

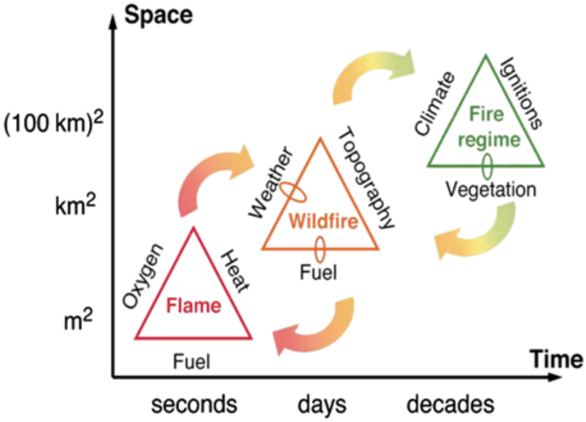

Fig. 2.2 The scaling of the combustion process over time and space from Moritz et al. (2005)

replaced over time along pathways of disturbance adaptations, shade tolerance, and biophysical processes; Chap. 6). Missing from this diagram are the key biophysical processes that control fuels, namely deposition (fallen plant material often called litterfall) and decomposition (Chap. 6). The interactions of plant succession and endogenous and exogenous disturbances with biomass deposition and decomposition mostly govern fuel properties, fuelbed dynamics, and spatial distributions at local to landscape scales.

This brings up an interesting dilemma in that most fire behavior research has been done at the fuelbed or flame scale (Sullivan 2009a) often resulting in a scale mismatch between fuel management and fire behavior, because most fuel management issues demand a coarser scale of analysis (Keane et al. 2012a). Therefore, an overview of how fuels are defined in surface fire behavior models is needed to understand the current and past use of fuels.

2.2 Surface Fire Behavior Modeling

2.2.1 Fire Behavior Formulation

The great fires of 1910 created the first real need for an understanding of fire behavior and search for models to predict fire behaviors (Pyne 2001). US fire pioneers, such as Gisborne (1927) and Hawley (1926), linked empirical evidence with observed fire characteristics to explain the behavior of fire. Later, Curry and Fons (1938) and Fons (1946) attempted to describe fire spread using more theoretical, physically based relationships. However, it quickly became evident to fire managers that these physical relationships were too complex to easily apply on the fire line. Fire managers needed some way to easily estimate fire behavior to more effectively manage wildfires, predict effects of prescribed burns, and save firefighter's lives.

Table 2.1 Fuel characteristics and properties used as input parameters for basic fire behavior equations at the three scales of fuelbed description

Scale	Symbol	Parameter	Notes
Fuel particle	d	Particle diameter	Often stratefied into classes
	SAVR	Surface-area-to-volume ratio (m^2/m^3)	Called SAVR in this book but is also called σ in many fire texts
	ρ_p	Particle density (kg m^{-3})	Generally 500 kg m^{-3} (32 lb ft^{-3})
	FMC	Moisture content (fraction)	Dry weight basis kg moisture per kg wood
	S_e	Effective mineral content (fraction)	Generally 0.010 (kg minerals – kg silica) per kg wood
	S_T	Total mineral content (fraction)	Generally 0.0555 kg minerals per kg wood
	h	Heat content	Often 18586 J kg^{-1} (8000 BTU lb^{-1})
Fuel component	W	Fuel loading (kg m^{-2})	Oven-dried fuel weight; a highly dynamic input
	ρ_b	Component bulk density (kg m^{-3})	Generally an integrated average across the fuel component and includes air space
	M_x	Dead fuel moisture of extinction (fraction)	Live fuel moisture of extinction is not in the basic model; another highly dynamic input
	δ	Surface fuel layer depth (m)	Mean fuelbed value
	β	Surface fuel layer packing ratio (dimensionless)	See Table 2.2 for estimation

Critically needed was an estimate of how fast a fire burned, called rate of spread (R), because this was identified as an important characteristic in firefighter deaths (Barrows 1951). An additional estimate of how hot a fire burned, called fire line intensity (I) or the rate of heat release per unit length of the fire front, was needed to determine when a fire is too hot to fight. Byram (1959) defined fire line intensity, I, as:

$$I = \frac{hW_c S}{60} \tag{2.4}$$

where h is the heat yield of the fuel (kJ kg^{-1}), S is the forward rate of spread of the fire (m min^{-1}), and W_c is the weight of fuel consumed in flaming combustion (kg m^{-2}). The number 60 is a conversion factor so that the units for I are kW m^{-1} (kJ m^{-1} min^{-1}). Fuel weight consumed (W_c) depends on initial fuel loading (W; kg m^{-2} dry weight). Both loading (W) and heat yield of fuel (h, often called heat content) are the first two important fuel properties for predicting fire behavior (Table 2.1). Linking fire intensity (I) with spread rate (R) provided a means to evaluate the potential to suppress the fire using the fire characteristics chart (Andrews and Rothermel 1982).

Rothermel (1972) and his team used results of this previous work to create the quasi-empirical mathematical model that is now integrated into a wide variety of US fire behavior prediction systems, such as BEHAVE (Andrews 2014), FARSITE (Finney 1998), and FIREHARM (Keane et al. 2010). This model has been extensively modified, adjusted, and refined (Albini 1976; Andrews 1986), but the main equation for fire spread prediction still takes the general form (Table 2.2):

Table 2.2 Equations of the basic fire spread model taken from Rothermel (1972) and Albini (1976) (courtesy of Pat Andrews) and converted to metric units

Variable	Equation	Equation number Rothermel (1972)
Rate of spread (m min^{-1})	$R = \frac{I_R \xi (1 + \phi_W + \phi_S)}{\rho_b \varepsilon Q_{ig}}$	(Eq. 52)
Reaction intensity (kW m^{-2} min^{-1})	$I_r = \Gamma' w_n h \eta_M \eta_s$	(Eq. 27)
Fire line intensity (kW m^{-1} fire line)	$I_b = \frac{12.61_r R}{60(SAVR)}$	Added later
Optimum reaction velocity (min^{-1})	$\Gamma' = \Gamma'_{max} (\beta / \beta_{op})^{[A} e^{A(1 - \beta/\beta_{op})]}$, where $A = 133(SAVR)^{-0.7913}$	(Eqs. 38, 39)
Maximum reaction velocity (min^{-1})	$\Gamma'_{\text{max}} = (SAVR)^{1.5} (495 + 0.0494(SAVR)^{1.5})^{-1}$	(Eq. 36)
Optimum packing ratio (fraction)	$\beta_{op} = 3.348(SAVR)^{-0.8189}$	(Eq. 37)
Packing ratio (fraction)	$\beta = \frac{\rho_b}{\rho_p}$	(Eq. 31)
Oven-dry bulk density (kg m^{-3})	$\rho_b = \frac{w_o}{\delta}$	(Eq. 40)
Net fuel loading (kg m^{-2})	$w_n = w_o (1 - S_T)$	(Eq. 24) replaced by Albini (1976)
Moisture damping coefficient (fraction)	$\eta_M = 1 - 2.59 r_M + 5.11 (r_M)^2 - 3.52 (r_M)^3$, where $r_M = FMC / M_x$ (max = 1.0)	(Eq. 29)
Mineral damping coefficient (fraction)	$\eta_s = 0.174 S_e^{-0.19}$ (max = 1.0)	(Eq. 30)
Propagating flux ratio (fraction)	$\xi = (192 + 0.2592(SAVR))^{-1e[(0.792 + 0.681(SAVR)^{0.5})(\beta + 0.1)]}$	(Eq. 42)
Wind factor (fraction)	$\phi_w = C U^B (\beta / \beta_{op})^{-E}$, where $C = 7.47 e^{(-0.133(SAVR)^{0.55})}$; $B = 0.02526(SAVR)^{0.54}$; $E = 0.715 e^{[-3.59 \times 10^{-0.4} (SAVR)]}$	(Eq. 47–50)
Slope factor (fraction)	$\phi_s = 5.275 \beta^{-0.3} (\tan \phi)^2$	(Eq. 51)
Effective heating number	$\varepsilon = e^{(-138/SAVR)}$	(Eq. 14)
Heat of pre-ignition (kW kg^{-1})	$Q_{ig} = 250 + 1116 FMC$	(Eq. 12)

$$R = \frac{I_{\mathrm{r}}\xi(1+\phi_{\mathrm{W}}+\phi_{\mathrm{s}})}{(\rho_{\mathrm{b}})(\varepsilon)(Q_{ig})} \tag{2.5}$$

where I_{r} is reaction intensity, ξ is the propagating flux ratio (dimensionless), φ_{w} is a scaling function for wind (number between zero and one), φ_{s} is a scaling function for slope, ρ_{b} is the bulk density of the fuelbed (kg m^{-3}), ε is the effective heating number, and Q_i is the heat of pre-ignition (kJ kg^{-1}; Table 2.2). Reaction intensity (I_r) can be estimated by the amount of fuel consumed (W_c) and that fuel's heat content (h) using a reformulation of the Andrews and Rothermel (1982) relationship:

$$I_{\mathrm{r}} = \frac{W_{\mathrm{c}}h}{t_{\mathrm{r}}} \tag{2.6}$$

where t_{r} is the residence time (min) that is computed from the Anderson (1969) empirical relationship:

$$t_{\mathrm{r}} = \frac{12.595}{\mathrm{SAVR}} \tag{2.7}$$

where SAVR is the characteristic surface-area-to-volume ratio (m^{-1}) of the fuelbed. SAVR is the third important fuel property because it is in the majority of fire behavior calculations (Table 2.2). The characteristic SAVR is estimated from the weighted averages across all surface fuel components specified in the model and the SAVR values for each fuel component is estimated as an average for each particle using the diameter in the following equation:

$$\mathrm{SAVR} = \frac{4}{d} \tag{2.8}$$

where d is the average diameter of the particles in the fuel component (m). Particle diameter is the fourth important fuel property because it is related to SAVR and it is used to estimate loading. The next important fuel property is the parameter ρ_{b} (bulk density of the fuelbed, kg m^{-3}). This parameter is also used to estimate the effective heating number (ε) in Eq. 2.5 using the empirical Rothermel (1972) relationship:

$$\in = \frac{\rho_{\mathrm{b}}}{\rho_{\mathrm{e}}} = e^{\frac{-138}{\mathrm{SAVR}}} \tag{2.9}$$

where ρ_{e} is the effective fuelbed bulk density (kg m^{-3}; Table 2.2). However, the effective heating number can also be accurately estimated from SAVR, which is used to represent fuel particle size (Eq. 2.8). Fuelbed bulk density (ρ_{b}) is often calculated from the following equation:

$$\rho_{\mathrm{b}} = \frac{W}{\delta} \tag{2.10}$$

where δ is the fuelbed depth (m), the sixth important fuel property, and W is fuelbed loading (kg m^{-2}).

In the Rothermel (1972) algorithms, reaction intensity (I_{r}) is computed from another equation (see Table 2.2):

$$I_{\mathrm{r}} = \Gamma' W_n h \eta_m \eta_s \tag{2.11}$$

where W_n is fuel loading (kg m^{-2}) adjusted for the mineral content, Γ' is the reaction velocity (a dynamic variable that represents the rate and completeness of fuel consumption), and η_m and η_s are damping functions to account for the effect of fuel moisture and mineral content, respectively, on combustion (equations for all variables in Table 2.2). Two fuel properties have a major effect on reaction intensity. Increasing fuel moisture and mineral content decreases I_{r} using the damping coefficients η_m and η_s that are represented by empirical relationships. The coefficient η_m is calculated using an empirical polynomial regression equation where the only variable is the ratio of the fuel moisture content (FMC; %) to the moisture of extinction (M_{x}; %; Eq. 29 in Rothermel (1972); see Table 2.2). These two fuel moisture variables are the seventh and eighth important fuel property. The mineral content damping coefficient (η_s) is calculated using the following empirical equation developed by Philpot (1970):

$$\eta_s = 0.174 S_e^{-0.19} \tag{2.12}$$

where S_{e} is the effective mineral content calculated as the amount of silica in the fuel component minus the mineral content (S_{T}). Mineral content (S_{e} and S_{T}) is the ninth important fuel property. Fuelbed compactness is another important fuelbed property affecting I_r and it is often represented by the packing ratio (β) defined by:

$$\beta = \frac{\rho_{\mathrm{b}}}{\rho_{\mathrm{p}}} \tag{2.13}$$

where ρ_{p} is the average particle density of the particles that comprise the fuel component (kg m^{-3}), the eleventh important fuel property (Table 2.1).

2.2.2 Fire Behavior Assumptions

To simplify the spatial complexity of the combustion process, early fire scientists had to make the assumption that fire spread can be represented by the movement of a flame across a semipermeable surface using a one-dimensional point model (Fig. 2.3; Rothermel 1972). This would have been a good assumption if (1) fuels were homogeneously distributed over the scale of a burning, (2) fires act at only one scale, and (3) the scale of the fire matched the scale of the fuels. But unfortunately, the distribution, condition, characteristics, and consumption of burnable biomass are highly complex over space and time (Frandsen and Andrews 1979; Chap. 6). Therefore, the scale mismatch between fire modeling and fuel properties may bias the simulation of fire in a one-dimensional approach. For example, an input fuel parameter that varies greatly over the small scales of fire spread, such as fuelbed

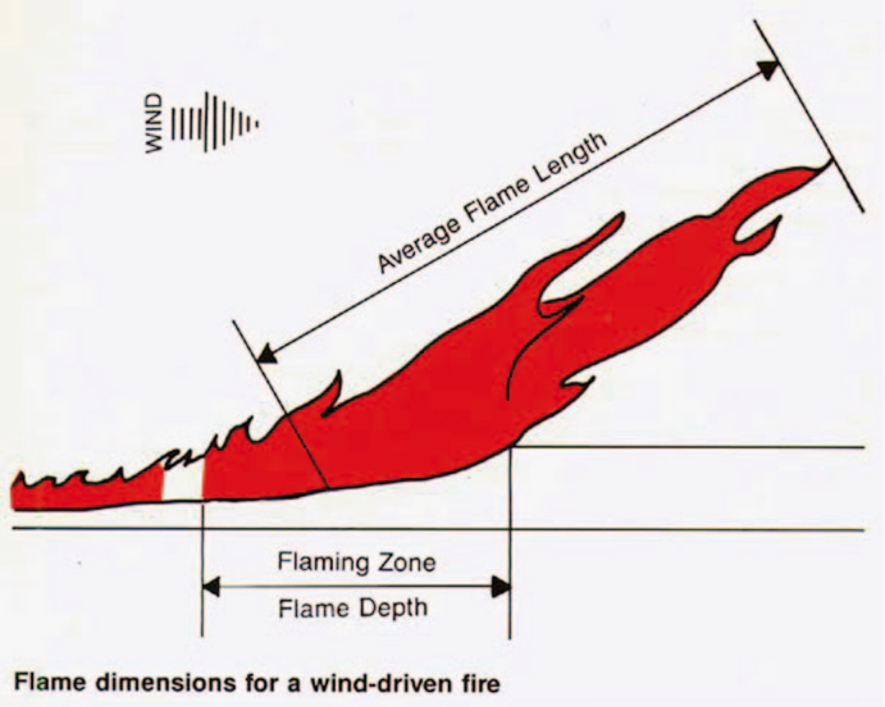

Fig. 2.3 The theoretical flame of fire spread used in the development of the one-dimensional fire spread models

bulk density, may not provide great predictive power when fire is simulated for one point in space.

Another great need for fire behavior simulation was to predict fire effects. Byram (1958) noted the importance of predicting the impact of fire on living vegetation, and Rothermel and Deeming (1980) noted fire behavior was critical for predicting fire effects. Yet ironically, fuel inputs to most fire models were engineered to fit combustion relationships without an ecological context. Successful prediction of fire effects requires that the model to be designed so that the inputs make ecological sense (Keane and Finney 2003) and that the outputs are germane to the assessment of fire effects. Grouping all log biomass into one size class, for example, ignores the great importance of log size on fuel properties and subsequent combustion, and, more importantly, on the effects of burning different-sized logs on soil heating and smoke production. Moreover, some fire effects models use fuel properties that are not used in fire behavior simulation algorithms (Trakhtenbrot et al. 2014). Mechanistic fire-caused tree mortality models, for example, use thermal conductivity to simulate heat flow through bark (Mitchell 2013).

And last, it is important to note that most operational fire behavior models are quasi-empirical in design (Sullivan 2009b) in that they predict fire spread and intensity using physically based statistical algorithms. As Finney et al. (2013) mention, there really is no physical theory of fire spread, so many numerical representations of the physical process of combustion are commonly empirical. This means that most fire behavior modelers had to make broad assumptions of the combustion process, specifically with respect to the physical description of fuels, and these assumptions may be inappropriate for a given physical process or scale of application. The fuel property surface-area-to-volume ratio (SAVR) is a good example. Finney et al. (2013) show that SAVR may not be the principal factor governing boundary layer thermal dynamics and vertical surface flow length may be more important, yet SAVR is an important fuel property used to simulate fuel effects on thermal dynamics (Table 2.2). Therefore, many fuel properties and components were selected because they best correlated to fire processes using limited empirical relationships and it was assumed that they are representative of the causal mechanisms governing fire behavior everywhere. This results in an imperfect fit between the ecology of fuels and the prediction of fire behavior, and it is the primary reason why the study of fuels is so difficult. Fuel description and management will continue to be difficult when fuels are described in the context of fire behavior without a theory of fire behavior and without being fully integrated with ecology.

The above description of the representation of fuel in fire behavior modeling is mostly limited to the US fire behavior prediction systems and is meant only to generally describe those fuel properties that are commonly used in fire behavior and effects simulation. The list of eleven variables (Table 2.1) is by no means exclusive; there are other fire behavior models in the world that use additional fuel-related variables in their structure (Sullivan 2009a, b; Linn 1997; Parsons et al. 2010). Moreover, there are many other fuel particle and fuelbed properties that are important to the field of wildland fuel ecology, such as degree of rot, particle length, and fuelbed cover, that are not discussed here. However, this list (1) probably represents those fuel properties used across most of the world's fire behavior modeling systems, (2) is perhaps the most important for the merging of fire behavior with ecology, and (3) contains properties that can be measured by fire behavior practitioners and wildland fuel managers. These properties are discussed below fuelbed scale.

2.3 Surface Fuel Properties

Past fuel studies have identified the fundamental properties of fuels as quantity, size, shape, arrangement, continuity, and pattern (Bebi et al. 2003; Ottmar et al. 2007), but this classical list has many limitations. First, there are scale inconsistencies, in that some properties refer to individual particles, while others refer to all particles in fuel components, layers, and fuelbeds. Second, missing are some physical properties that describe the role of the fuel in the combustion process, especially in the context of fire behavior (see Sect. 2.2). There is also a missing linkage between many of these fundamental properties and how they are used to simulate fire or how they are employed in fire and fuel management. For example, arrangement remains unaddressed in point-scale fire models. And last, this list is missing critical metrics and variables that can be used to quantify the properties. This chapter discusses the quantity (loading), size, and shape of surface fuels in the following section by scale and specific property. Arrangement, continuity, and pattern are discussed in detail in Chap. 6. While some important fuel parameters listed in Table 2.2 refer to the properties of a fuel component, the component parameter is often computed as an average across particles within the component. Therefore, each fuel property is discussed at the scale of measurement rather than the scale of model input.

2.3.1 Particle Properties

2.3.1.1 Particle Diameter (*d*)

While fuel particle diameter (d) is a critical fuel parameter for fire behavior modeling, it is even more important in sampling for fuel loading (W). Thomas (1953), for example, mentioned that the duration of burning is related to stick diameter by approximately the 1.5 power. However, use of diameter in most fire and fuel applications may be overgeneralized because nearly all fire behavior models assume woody fuel particles are circular in cross section and use an assumption of a cylinder to estimate volume for other fuel properties, such as SAVR (Eq. 2.13) and density (Keane et al. 2012b). Most woody fuel particles are not cylinders, but rather, they are complicated volumes of highly variable cross sections and contorted lengths. Moreover, particle diameters are not static; they change with weather conditions, often becoming thicker when wet, and cracked when dry, making diameter measurements difficult and further complicating the estimation of SAVR. Distributions of diameters and lengths are also highly variable across woody particles. The assumptions of circular cross sections and frustum volumes are necessary due to current fire behavior modeling and fuel sampling limitations, but future efforts should explore methods for estimating SAVR and particle volume by other means.

Diameter measurements are required for many fire modeling and fuel sampling techniques (Chap. 8). Measuring particle diameter is relatively easy and is usually often done with a ruler, caliper, or diameter tape. However, many have found that these measurements are often too coarse for accurate fuel particle volume estimation, especially for fine woody fuels, because of the large variation of diameters across a fuel particle and the assumption that the particle is a cylinder or frustum (Brown 1970a). Using a single particle diameter often complicates efforts to evaluate loading sampling method accuracy and precision because a major source of uncontrolled error comes from the circular cross section assumption (Keane and Gray 2013; Sikkink and Keane 2008).

2.3.1.2 SAVR

SAVR (m^{-1}) is defined as the area of a particle surface (m^{-2}) divided by the volume of that particle (m^{-3}), but it is often indirectly estimated from particle diameter (d) using Eq. 2.13. Particles that are thick, such as logs, have low SAVR values (less than 1.0 m^{-1} for large logs), whereas thin particles that are long and wide, such as leaves, have high values (over 2000 m^{-1} for grass blades and pine needles). SAVR is a fuel property that indirectly characterizes particle geometry (shape), and this corresponds to the particle's importance in fire science. Particles with high SAVR (e.g., foliage) are more flammable and easier to ignite than low SAVR particles (e.g., logs; Pyne et al. 1996). SAVR indirectly represents the effect of fuel size on combustion processes. It also represents the rate of response of fuel particles to temperature and moisture fluctuations; particles with high SAVR values lose heat and moisture more quickly than particles with lower SAVR values (Brown 1970b).

SAVR is extremely difficult to measure accurately because most fuel particles are complex in geometry. The most common way to measure SAVR is to use the simple formula developed by Brown (1970b) where the fraction of particle perimeter divided by the average cross-sectional area taken for cross sections along the length of the particle. This technique requires an assumption of a geometric shape of the cross section, and most efforts assume a circle to represent the fuel particle volume, although many have used other shapes for needles, leaves, and grass blades. However, most fuel particle cross sections are difficult to describe with any general geometric shape, rather, they are complex amorphous forms. Another method is to estimate volume by submerging the particle in a liquid and measuring the displacement of the liquid, and measuring the surface area by assuming some geometric shape and measuring various dimensions to estimate area. A more complex technique would be to measure the rate of drying of the fuel particle and correlating that rate to surface area. The problem with all of these techniques to estimate SAVR or density is that particles are constantly changing in response to endogenous and exogenous biophysical processes. All fuel particles are in some state of decay, and the degree of decay and its distribution across a particle can affect SAVR. Moreover, fuel particles are constant changing shapes in response to fluctuations in moisture content, temperature, and relative humidity as mentioned above. These responses sometime result in the fragmentation of the particle, which then increases surface area and SAVR. This dynamic quality of fuel particles results in greater variability in the estimation of particle SAVR.

2.3.1.3 Particle Density (ρ_p)

Particle density is the dry weight of the particle per unit volume (kg m^{-3}). The term specific gravity is also used to represent particle density; specific gravity is the density of a substance relative to the density of water at a specific temperature and pressure. One needs to multiply specific gravity by 1000 to convert to density (e.g., 0.42 specific gravity is 420 kg m^{-3}).

Particle density is measured using variations of two techniques. The particle is always oven-dried and weighed to determine mass. Then there are two techniques for measuring volume. The first technique calculates volume by assuming various geometric shapes and using diameters and lengths to define shape dimensions (see

Sect. 2.3.1.1). However, there are great measurement errors when fuel particles are small because of highly variable fuel dimensions and inaccurate measurement procedures (Keane et al. 2012b). The other technique involves dipping the particle in liquid and calculating the displacement in volume or mass as mentioned above for SAVR. This technique is more accurate, but there are several problems that must be addressed to get more precise measurements. First, care must be taken to ensure the particle does not absorb the liquid, and this is done in a number of ways, including dipping the particle in wax or some other substance that prevents absorption or using a liquid that will not be readily absorbed by the particle. Displacement by weight can be estimated if the specific gravity of the liquid is known, while displacement of volume is somewhat problematic in that it is difficult to accurately estimate displaced volume for small and large particles.

Particle density is another property that is difficult to measure because of its high variability within a particle, across fuel types, and among fuelbeds. The density of some particles, especially woody fuels, can vary substantially along the length of the particle. Logs, for example, can be in various stages of decay along their lengths because of their contact with the ground resulting in a wide variety of densities within one particle. Most material in the litter fuel component often exists as foliar material in various states of decomposition because of their position in the vertical litter profile. And, similar to SAVR, particles are constantly changing in volume in response to environmental conditions resulting in changes in density. And each fuelbed results from a unique combination of disturbance history, vegetation development, and moisture regime, all influencing particle densities.

2.3.1.4 FMC and Moisture of Extinction (M_x)

FMC is one of the most important and dynamic fuel properties, so it is discussed in a separate chapter (Chap. 5) and will not be detailed here. Some refer to the moisture level in wildland fuel as the *fuel state* or *condition* (DeBano et al. 1998), and some refer to those fuels that can burn because they are dry enough as *available fuels* (Brown and Davis 1973). Fuel moisture provides the important link to estimate fire danger (Deeming et al. 1977), and is perhaps one of the most critical inputs in fire behavior prediction models (Andrews 1986; Table 2.2). Fuel moisture also is important to many other ecological processes, such as decomposition, evapotranspiration, and nutrient cycling.

The moisture of extinction (M_x) is the moisture content at which combustion cannot be sustained (moisture above which fire does not burn; Rothermel 1972), and greatly depends on the type, quantity, and arrangement of fuels and their interaction with weather, mainly wind. Dead woody fuels are often assigned M_x of 30 % while M_xs for live fuels are much harder to quantify. This property is actually a static parameter used in fire behavior modeling algorithms at the fuel component level (see Table 2.2) to drive combustion to zero at high moisture contents (Rothermel 1972). It would be difficult to estimate M_x under field conditions because it would change with ambient weather (e.g., temperature, humidity, incident radiation) and particle qualities (e.g., rot, density, shape, size), and live fuel plant condition (e.g., phenology, moisture stress, size). In reality, the distribution of M_x in a typical fuelbed could be quite variable and difficult to accurately quantify for operational fire management.

2.3.1.5 Mineral Content (S_e, S_T)

Mineral content (S_e and S_T depending on the equation in Table 2.2) has a profound impact on fire behavior (Philpot 1970; Eqs. 2.9, 2.10). Biomass with high mineral content, such as duff and slash fuel, will tend to burn slower and have a higher proportion of burning in smoldering combustion, often resulting in reduced combustion. In fact, fire retardant depends on this relationship to be effective; the primary purpose of retardant is to retard the spread of fire by increasing mineral content, thereby depressing fire spread (Giménez et al. 2004). The mineral content (S_T) is the percent of the total weight per unit volume of fuel particle that is inorganic material or mineral (i.e., not composed of molecules of C, H, and O). It is usually estimated by burning a fuel particle of known dry weight and weighing the ash that is left after complete combustion; the weight of ash divided by dry weight of the wood is the mineral content. The effective mineral content (S_e) is the mineral content with the proportion of silica removed (Table 2.2).

Since minerals are key nutrients needed in plant photosynthesis and respiration, they become incorporated into biomass, and each fuel particle has its own relatively static mineral content (around 5 %). Wood in woody fuels is usually 1 % mineral, while the bark can have ten times that amount (Ragland et al. 1991). Needles have fewer minerals (0.1 %), but mineral content often increases with needle age (Weikert et al. 1989). Particles near or in contact with the ground will usually have higher mineral contents because of the diverse processes involved in decomposition (Chap. 6); soil macrofauna break down organic material and often incorporate mineral soil onto the downed fuel particles. And, minerals will also tend to accumulate in the duff layer as microbes process the organic material and leave the minerals to collect in the duff (Chap. 6). As a result, ground fuels usually have the highest mineral contents, often greater than 10 %, partially explaining why ground fuels mostly burn in smoldering combustion. Keane et al. (2012b) found mineral contents were the highest in the smallest fuel particles with litter and duff having 10–50 % mineral contents, 1 h woody having 2–5 %, 1,000 h woody having 0.1–0.8 % for forest and rangelands of the northern Rocky Mountains, USA. However, these mineral contents varied greatly from site to site, and stand by history.

2.3.1.6 Heat Content (h)

The heat content (h) is the heat yield of the fuel per unit mass (kJ kg^{-1}) and, when multiplied by loading (W), is used to compute fire intensity (Eq. 2.4). This is best described as the heat released from the combustion of the gases evolved in the ignition phase (see Sect. 2.1.2) and is also called the effective heat content (Shafizadeh et al. 1977). The heat content of wildland fuel is mostly dependent on the chemical composition of the material being burned. While the majority of fuel is cellulose and lignin, there can be other chemical constituents of fuel that affect heat content. Biomass with high mineral contents, for example, will have lower heat contents (Susott et al. 1975). However, there are many chemical compounds in biomass that may increase heat content. Oils, resins, and proteins may increase heat contents in foliage and other parts of the plant (Philpot 1969). Moisture content also governs the amount of heat given off from burning fuels (Chap. 5) because heat must be used to vaporize the free and bound water in live and dead fuel particles.

Wildland fuel heat content values are quite different within and among fuel types, season, and the intensity of the fire when it is burned. Foliage usually have higher heat contents (20–21 MJ kg^{-1} or 8700–9400 BTU lb^{-1}) than twigs and stems (18–20 MJ kg^{-1} 8300–8700 BTU lb^{-1}), but this relationship is quite different across species, age, and dead versus live fuels (Philpot 1969). Kelsey et al. (1979) found that the heat content of wood ranged from 19.3 to 22.5 MJ kg^{-1} (8300–9700 BTU lb^{-1}), while bark heat content values were substantially higher ranging from 20.2 to 25.3 MJ kg^{-1} (8700–10,900 BTU lb^{-1}), and foliage heat contents were in between 20.1 and 22.4 MJ kg^{-1} (8700–9700 BTU lb^{-1}). And, the heat content might change over the course of a fire season. Philpot (1969) found that the heat content for chamise shrub leaves were lowest in the spring (~21 MJ kg^{-1} or 9100 BTU lb^{-1}) and increased to 23.5 MJ kg^{-1} (10,100 BTU lb^{-1}) in the autumn. And last, the heat content of fuels burned under flaming combustion might be quite different than when fuels are burned under smoldering combustion (Susott et al. 1975). Yet despite this high variability, most fire models use a constant value for heat content. As an example, a constant value of 18 MJ kg^{-1} (8000 BTU lb^{-1}) has been assigned to all but two of the Scott and Burgan (2005) fire behavior fuel models.

Heat content is usually measured using a bomb calorimeter using a method where a standardized measure of fuel is placed into a constant volume calorimeter and electrical energy is used to ignite the fuel. As the fuel is burning, it heats the surrounding air, which expands and escapes through a tube that heats water outside the tube. The change in the temperature of the water allows for calculating the amount of heat generated from the fuel.

2.3.1.7 Other Important Particle Properties

There are several other important fuel particle properties that are not directly used in fire behavior modeling, but they are still important in fuel science and management. Particle *shape* or the general geometry of a fuel particle is important because it is used to define a geometric form for which an equation can be used to calculate volume that is then used to estimate density and mass. Shape is also used to classify particles into fuel components and to parameterize fuel components for modeling. Particle shape is also important in fuel moisture dynamics, ignition processes, and combustion.

Particle *thermal conductivity* is a physical measure of the heat conduction potential of fuel or how fast heat can travel through fuel. Thermal conductivity has the complex units of W m^{-1} °K^{-1} or Joule sec^{-1} m^{-1} °K^{-1} or kg m sec^{-3} °K^{-1}, therefore having representations of energy, mass, time, length, and temperature. Thermal conductivity is most often used to describe solid fuel particles, but it can also be modified to describe heat transfer through porous fuelbeds, layers, or components. Estimates of thermal conductivity for duff, for example, are often used to simulate heat and temperature dynamics in the soil layer as a result of surface fire (Campbell et al. 1995). Bark thermal conductivity is used to estimate how hot and fast heat penetrates live tissue to estimate plant mortality (Reinhardt and Dickinson 2010). In general, most fire applications that require an estimate of thermal conductivity are for research purposes or specialized fire effects models (Reinhardt et al. 1997).

The *chemical content* of fuel particles is also important to most of the fuel properties presented here and also for other fuel properties that are input to some fire and fuel management applications. Oils and resins in some fuel particles may increase heat content (see Sect. 2.3.1.6; Philpot 1970), while high concentration of minerals in leaves and some wood may reduce flammability and dampen combustion (see Sect. 2.3.1.5; Whelan 1995). Other aspects of chemical composition may be important from a human health standpoint. Fuel particles might contain mercury or radioactive elements that, when burned, could create hazardous smoke emissions that might impact air quality (Canham and Loucks 1984). The relative concentrations of organic compounds, such as cellulose and lignin, influences those fuel properties that control live and dead fuel moisture dynamics, such as permeability and hygroscopy (affinity of cell walls to hold water; Chap. 5) and dictate rates of decomposition (Chap. 6).

2.3.2 Fuel Component

Most fuel component properties are quantified from a statistical summary of the fuel particle properties, which is often an average across a fuel component. For example, the 10 h woody fuel component (Chap. 3) is defined as downed deadwood particles with diameters greater than 0.6 cm (0.25 in) and less than 2.5 cm (1 in), so the average diameter (d) of the 10 h class is estimated from field measurements (Brown 1970a) and SAVR is estimated from d and ρ_p (Eq. 2.13). However, there are two fuel component properties that are measured directly and not estimated from particle properties.

2.3.2.1 Loading (W)

Loading is quantified as the dry weight mass of the fuelbed or fuel component per unit area. Loading estimates are reported in dry weight to eliminate moisture contributions to weight estimates, which can vary wildly over a fire season. The units used to represent loadings are quite important in fuel management because they are the context in which many people visualize the weight of fuel loads. Traditionally, loadings were assigned imperial units of tons acre^{-1}, but it is difficult for many fire professionals to envision what a ton of any fuel component looks like, let alone envision how it is distributed across an area as large as an acre. Moreover, the fuel components comprising a fuelbed have different scales of distribution (Chap. 6), so large areas are rarely needed to visually estimate the loading of fine fuels. Many studies now use SI units of kg m^{-2} for most fuel components (Keane and Dickinson 2007) because they are more easily visualized (it's easier to imagine a kilogram or 2.2 pounds of fuel over a square meter of ground than a ton of fuel over an acre). However, these units may be inappropriate for CWD and canopy fuels. Surface and canopy fuel loading measurement techniques are discussed in detail in Chap. 8.

Fuel loading is the primary fuel property discussed in this book because it is used extensively in wildland fire management for many purposes. The calculation of fire intensity, for example, demands an estimate of fuel loading (Eq. 2.4), and fire intensity is perhaps one of the most important fire behavior characteristics for estimating fire effects (Reinhardt et al. 2001). Loading is also used to estimate smoke emissions which directly affect human health and wellness. Loading often correlates to both vertical and horizontal fuel connectivity; undisturbed fuelbeds with high loadings are more likely to have greater canopy fuels and are more likely to be connected to fuelbeds with high loadings. Loading is also important for issues outside of fire science, such as habitat for small mammals, site productivity, carbon dynamics, and soil erosion.

2.3.2.2 Bulk Density (ρ_b)

The bulk density of a fuel component is the mass of the fuel component material divided by the volume of space within which it resides (Fig. 2.4a). Bulk density is different from wood or particle density (specific gravity) in that the volume includes the empty space between fuel component particles. Bulk density is often used to represent fuel arrangement in vertical dimensions; canopy profiles, for example, display the vertical distribution of canopy bulk density for crown fire modeling (Bebi et al. 2003). Past studies often used bulk density to represent *fuel porosity* (Countryman 1969).

Bulk density has a number of uses in fire management. First, it is an input to some important fire modeling programs (see Table 2.2); canopy bulk density is used in FARSITE (Finney 1998) to simulate crown fire propagation (Chap. 4) and fuelbed bulk density (ρ_b) is used to simulate surface fire intensity (Eqs. 2.9, 2.13). Bulk density can also be used to describe the rate at which heat can travel through a surface fuel layer. Another common application is in calculating loading for those fuel components that are difficult to sample. Duff, litter, shrub, herb, and tree regeneration fuel component loadings, for example, are difficult to measure operationally, so many fire specialists use the volume method to approximate loading. In this method, the depth of a fuel component is visually estimated or measured as an integrated average across an area, and multiplying this depth by the area of consideration gives the volume which the component occupies. The loading of that component can then be estimated by multiplying volume by bulk density (details are given in Chap. 8). The problem with calculating loading this way is deciding the scale at which to measure loading. Should volume be calculated for the entire

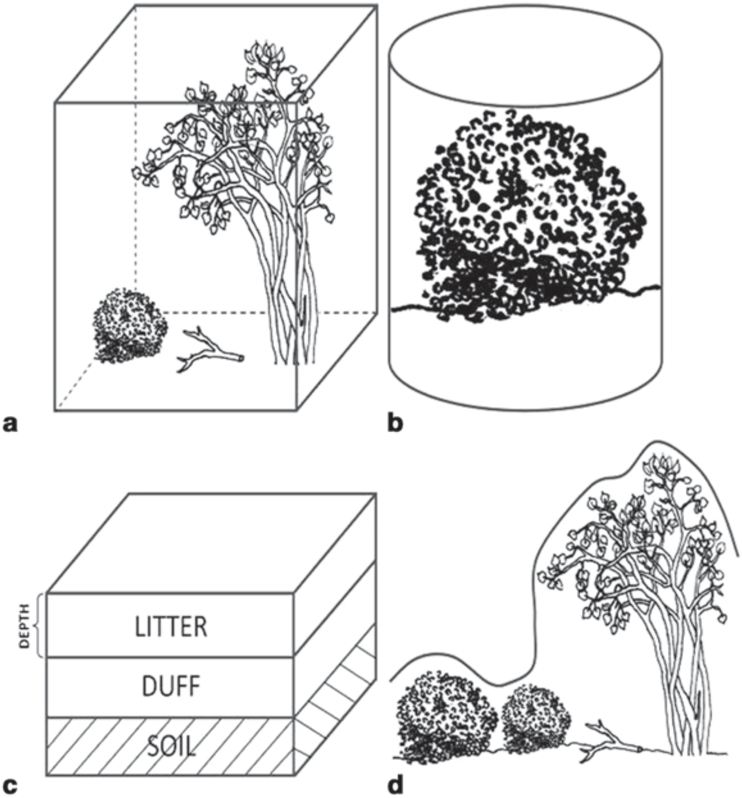

Fig. 2.4 Examples illustrating the various ways to calculate the bulk density of a fuelbed or fuel component. Bulk density is estimated as the mass of the fuel divided by volume. Volume is calculated as the area of concern times the height of the fuel making it scale dependent: **a** the volume is calculated from an estimate of depth across the fuelbed unit area; **b** the volume is calculated for the individual plant, particle, or component; **c** litter and duff bulk densities are more consistent because the depth is less variable across space; and **d** volume is calculated as an integrated average fuelbed depth

fuelbed (Fig. 2.4a), for each individual plant (Fig. 2.4b), or estimated from an average integrated height of plants in a fuelbed (Fig. 2.4d).

2.3.3 Fuel Layer

2.3.3.1 Fuel Layer Depth (δ)

Fuelbed depth is the thickness of the surface fuel layer (Tables 2.1 and 2.2). Many surface fuel components exist as layers of biomass above the ground, and fuelbed depth is the highest height of any fuel particle of any component integrated over the area of consideration. Fuelbed depth is an important parameter in fire behavior systems that use the Rothermel (1972) model (Andrews 1986; Andrews 2014) (Table 2.2), and, because of this, it is a parameter that is commonly adjusted to match observed with simulated fire behaviors in creating fire behavior fuel models (Chap. 7; Burgan 1987). Burgan (1987), for example, mentions that a fire behavior fuel model can be made more sensitive to wind by increasing fuelbed depth. Fuelbed depth is often used to describe only the depth of the surface fuel layer and it is mostly used to derive fuel bulk densities in US fire models (Eq. 2.10).

Fuelbed depth has little ecological value since it is so highly variable across space and time scales. Its greatest use is as input into point-level fire behavior models that simulate fire in one dimension, such as BEHAVE (Andrews 2014). Because of its scale problems and high variability, it is often difficult to obtain an accurate measurement of fuelbed depth. Initial attempts to accurately measure depth were to envision a virtual sheet over the top of the surface fuel layer and visually estimating the average height of that sheet (Jensen et al. 1993). Moreover, it is difficult to evaluate if widely spaced and distinctive fuel particles constitute part of the fuelbed. For example, should widely scattered shrubs or occasional large logs be included in the depth estimation (Fig. 2.4d). Fruiting stalks on grass and forbs, as another example, are widely scattered and are easily blown by wind because they are often taller than the plant's foliage, making it quite difficult to determine if fruiting stalks contribute to fire spread and are therefore used to estimate depth.

2.3.3.2 Packing Ratio (β)

The packing ratio is an index used to represent the compactness of the fuelbed (Rothermel 1972). It is easily quantified as the ratio $\rho_b{:}\rho_p$ (fuelbed bulk density divided by particle density). This variable was invented to simulate the important damping effect of fuelbed looseness or compression on combustion using an index that is the fraction of fuelbed volume occupied by fuel. In fact, Catchpole et al. (1998) found that rate of spread decreased with the square root of the packing ratio. It had been observed that fire intensity and rate of spread occur at two extremes of compactness. Lack of fuel contagion causes loss of heat transfer in loose fuelbeds, while low air-to-fuel ratios and poor heat penetration result in lower spread rates and intensities in dense fuelbeds (Rothermel 1972). Between these two extremes is an optimum range of fuelbed packing where there is the best balance of air, fuel, and heat transfer, and this optimum packing ratio (β_{op} in Table 2.2) is greatly dependent on the fuel particles and how they are arranged in the fuelbed. Sandberg et al. (2007) modified Rothermel's (1972) equations to include a damping coefficient representing fuel compactness based on a new variable called relative packing ratio, which is the fuelbed packing ratio divided by the optimum packing ratio.

The main problem with packing ratio is that fuelbeds are often composed of many kinds of fuel particles from grass blades to woody twigs and logs; therefore, particle densities can be highly variable at very fine scales, resulting in highly variable packing ratios. Moreover, optimum packing ratios can vary across the year because of changes in plant phenology, the rate of decay, and abiotic interactions, such as grazing, trampling, and deposition (Chap. 6). As a result, the packing ratio, similar to fuelbed depth, is probably most applicable to one-dimensional fire behavior modeling and has little value in wildland fuel ecology. It would be difficult to quantify the packing ratio and its optimum in the field because of the mentioned scale issues and their temporally dynamic quality.

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