Chapter 1
Introduction

> *There is nothing more difficult to take in hand, more perilous to conduct or more uncertain in its success than …the introduction of a new order of things.*
> Niccolo Machiavelli

1.1 What Are Fuels?

Wildland fuels are named for the role they play when they are burned by a wildland fire. In a combustion science context, fuels are any combustible material (NWCG 2006). In an ecological context, these combustible materials are the live and dead organic matter that ecologists call *biomass*. Therefore, in this book, fuel is biomass. Some may feel that there are biomass pools that rarely burn, such as large tree boles and snags, and there are some biomass pools that are insufficiently distributed to support the contagious spread of fire, such as stumps and cones. However, most biomass material can combust and burn, especially under severe weather conditions (severe drought with high winds), so the "biomass is fuel" association seems appropriate for this book. There is often confusion between the singular and plural of fuel; in this book, the term *fuels* is used to describe all the different types and kinds of biomass in the aggregate, while *fuel* is used when referring to one particular type or kind of biomass.

Wildland fuels are the most important environmental factor in fire management. Brown and Davis (1973) mention that "fire ignition, spread, and intensity depend on fuel more than any other factor and it is the fuel that generates the fire behavior with which fire fighters must cope." Scott et al. (2014) say it more simply: "If there is no fuel, there is no fire." Countryman (1969) emphasized that "fuel is the only factor in the fire environment that humans can control." The importance of wildland fuels to fire management cannot be understated and the first step towards fully understanding fuels is learning the basic terminology used in this book.

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1.2 Basic Terminology

1.2.1 Basic Fuel Science Terms

In this book, the *fuelbed* is a general term for the complex array of biomass types for a given area and it is the coarsest scale of fuel description (Fig. 1.1). A comprehensive description of the fuelbed ultimately depends upon the spatial scale. Fuelbeds in forested ecosystems, for example, are somewhat larger than fuelbeds in nonforest ecosystems because the sizes of the trees dictate the scale of canopy fuels. Here, a spatial scale of about 100 m^2 is used to bound or describe a fuelbed regardless of the ecosystem (Fig. 1.1; Sullivan 2009a). This is somewhat greater than the scale of surface fire spread (1–2 m) but is more or less representative of vegetation dynamics (Hiers et al. 2009). Fuelbeds include all types of biomass types and their distributions, and, in this book, they have no vertical height limit, although many have used the term to specifically describe surface fuels. Fuelbeds have specific properties, such as composition, depth, and bulk density, that are used in both fire behavior prediction and fuel management (Chap. 2).

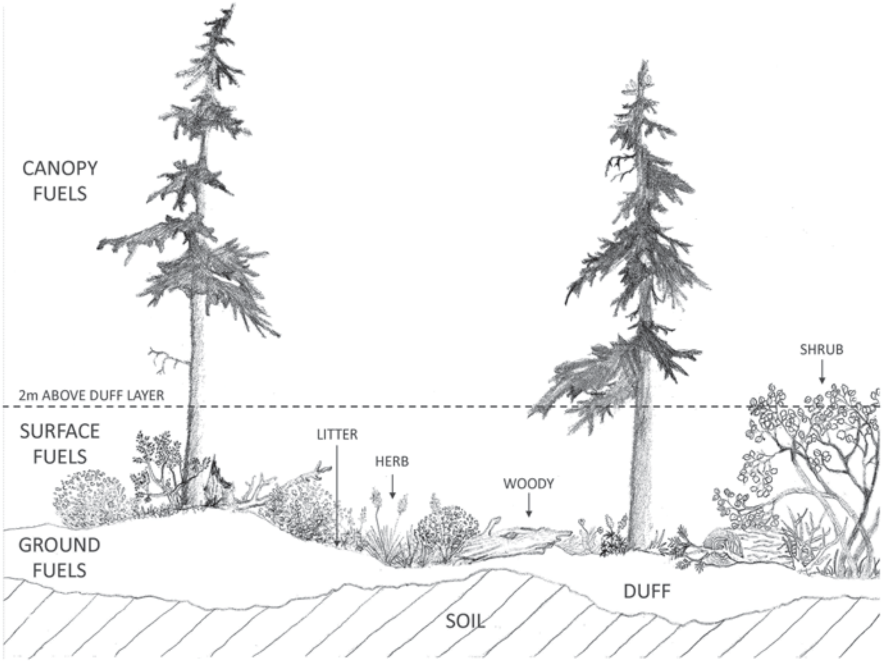

Fig. 1.1 The elements of a typical wildland fuelbed. The full representation of fuels within an area is called a fuelbed. Within a fuelbed, there are three fuel layers: ground, surface, and canopy. Each layer is composed of fuel types, such as litter, shrubs, grasses, and woody biomass in the surface fuel layer

The fuelbed is vertically stratified into three fuel *layers—ground, surface, and canopy* fuels. In this book, *surface fuels* are all biomass within 2 m above the ground surface (Fig. 1.1). This 2-m boundary is mostly arbitrary and was originally defined by several heights depending on the fire application; Brown and Davis (1973), for example, used a 4-ft height. *Ground fuels* are all organic matter below the ground line. The position of the ground line is highly contentious; some put it below the litter at the top of the duff because they feel that only the litter contributes to the propagation of the flaming front, while others put the ground line below the duff because it is incredibly difficult to distinguish between litter and duff in the field. In this book, litter is considered surface fuel while duff is considered ground fuel (Chap. 2). *Canopy fuels* are the biomass above the surface fuel layer. Some define the canopy as starting at 6 m (20 ft; NWCG 2006), while others define it as all tree biomass no matter the height. To be consistent, canopy fuels are defined as all biomass (e.g., shrub, moss, lichen, vine, dead material, and tree) that is higher than 2 m above the ground surface (Fig. 1.1). The term *aerial* fuel is also used to describe canopy fuel (Brown and Davis 1973).

Fuelbed layers are composed of finer-scale elements called fuel types and components (Fig. 1.2). *Fuel types* are general descriptions of the kinds of fuels comprising

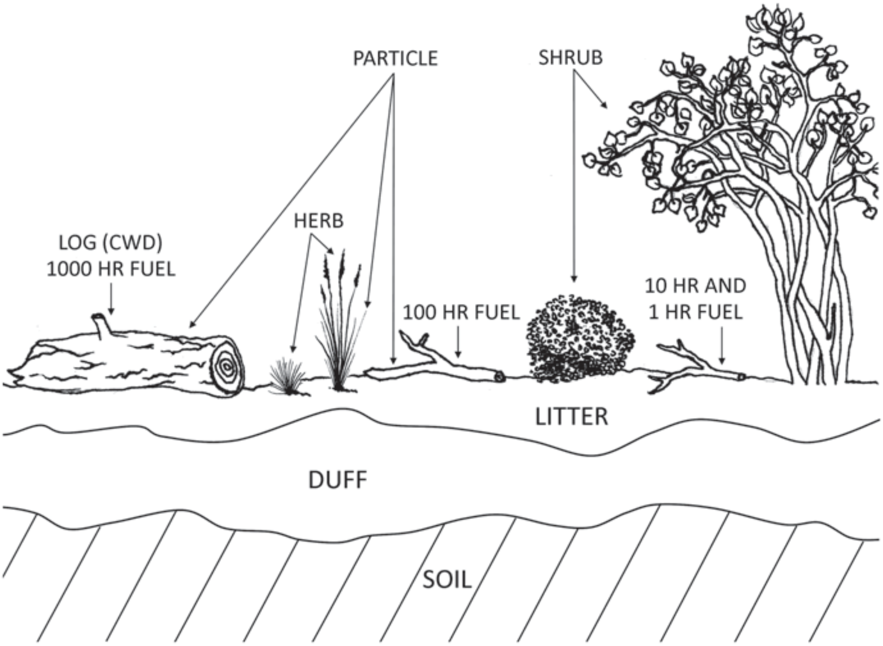

Fig. 1.2 Fuel types and fuel components. The quantitative description of these fuel types is called a fuel component (e.g., shrub component is all shrub biomass with branch diameters less than 5 cm). Each fuel type or component is composed of a set of fuel particles, such as intact or fragmented twigs, needles, or leaves

the fuelbed, whereas *fuel components* are fuel types that are qualitatively and quantitatively defined for specific purposes, mostly for fire behavior prediction. A fuel type might be "woody fuel," while a woody fuel component might be defined as woody fuel of a certain diameter size range (Chap. 3). Many fire practitioners refer to a fuel type as a general term for the dominant fuel of a fuelbed, such as a shrub fuel type describing a fuelbed where the loading is mainly shrubs. In this book, however, a fuel type is specific to the kind of fuel in a fuelbed independent of its loading, and the dominant fuel of a fuelbed is called a *fuel complex* (Bebi et al. 2003). A shrub fuel type would indicate that a fuelbed has some shrub biomass, while a shrub fuel complex would refer to a fuelbed that is dominated by shrubs. Similar to fuelbeds, fuel types and components also have specific properties, such as bulk density, loading (mass per area), and surface area, which are important inputs to fire behavior and effects models and important descriptors of fuel characteristics.

The finest scale of fuelbed description is the fuel *particle,* which is a general term that defines a specific piece of fuel that is part of a fuel type or component of a fuelbed (Fig. 1.2). For example, a fuel particle can be an intact or fragmented stick, grass blade, shrub leaf, or pine needle. Fuel particles have the widest diversity of properties, such as specific gravity, heat content, and shape (Chap. 2), and the properties of fuel components and fuelbeds are often quantified from statistical summaries of the properties of the particles that comprise them. For example, heat content of the herbaceous fuel component may be quantified by averaged heat content estimates across all particles (leaf blades) from all plant species that compose the herbaceous fuel type.

Wildland fuels are also defined as *dead* or *live* within any given fuel type, component, or particle. *Dead* fuel is suspended and downed dead biomass, often called *necromass* by ecologists, while, *live* fuel is the biomass of living organisms, mostly vascular plants (trees, shrubs, herbs), but also of mosses, lichens, and many other living organisms. The principle reason for this dichotomous stratification is to distinguish between two completely different mechanisms that control both fuel moisture (Chap. 5) and fuel dynamics (Chap. 6). Live fuel moistures, for example, are controlled by ecophysiological processes, such as transpiration, evaporation, and soil water, that vary greatly between species and climates, whereas dead fuels moistures are dictated by the interactions of the physical properties of the fuel (e.g., size, density, surface area) and exogenous factors, such as climate, topography, and shading vegetation. Some live fuels may contain dead fuels; trees, for example, may have live wood surrounding dead wood, such as in a healing fire scar. And, most fuelbeds consist of a complex distribution of live and dead fuels so determining live versus dead fuel in field situations can sometimes be difficult, often because some dead fuels may appear as live or they may be attached to live fuels. Mosses and lichens, for example, occur as complexes of live and dead fuels distributed throughout the surface and canopy fuel layers. In another example, dead branches can be attached to live trees, and live branches can be embedded in the litter. Besides moisture dynamics, live fuels also have significantly different physical properties than dead fuels with different particle size distribution, heat content, and mineral content (Chap. 3).

1.2.2 General Fuel Descriptions

Many general terms are also used to describe characteristics of a fuelbed. *Ladder fuel* is a term used to describe a vertical continuous layer of fuel that, when burned, can transport a surface fire into tree crowns to become a crown fire. Ladder fuel can be any live or dead biomass but most of the time it is tree and shrub foliage and small branches that extend down into the surface fuel layer or extend upwards into the canopy layer. *Flashy fuel* is a term often used to describe the finest fuel types that are most easily ignited and combust quickly, such as grasses, small twigs, and litter. *Sound* and *rotten* are two terms that are used to stratify the degree of decay in woody fuel particles although there isn't really a metric that can be used to determine what is a sound log and what is a rotten log. Sound woody fuels usually have greater particle densities, higher heat contents, and lower surface area to volume ratios than rotten fuels (Chap. 3).

Fuel *availability* is a term often used to describe the potential for biomass to burn. For fuel to be available, it must be dry enough to ignite and there must be enough of it to burn. In fact, some older fuel studies have often referred to wildland fuel as only the biomass that is available to burn. A similar term is fuel *condition* often defined as relative flammability of fuel based on type, environment, and mostly fuel moisture (NWCG 2006). Fuel *flammability* is defined as the relative ease at which fuels will burn regardless of amount (NWCG 2006; see Chap. 10). The problem with these three terms is that they are ambiguous, scale-dependent, and difficult to quantify, and therefore, they are often only used to qualitatively describe fuel types and fuelbeds. Some examples of the problems with these terms are illustrated with these questions: Is the fuel available if it only burns in smoldering combustion? Does fuel condition include continuity? Are fuels highly flammable if they produce high intensities? This ambiguity is partially a result of dynamic and complex ecological entities (biomass) being described in a combustion science context.

Fuelbeds are often given names that describe the factors involved in their creation. *Natural* fuelbeds are those fuelbeds created by vegetation development in the absence of disturbance. Endemic (within stand) disturbances may act on the vegetation to also create natural fuelbeds. However, the term "natural" is somewhat ambiguous and open to wide interpretation, so, in this book, the term *undisturbed* fuelbed is used to describe fuelbeds that haven't been affected by major disturbances. Major exogenous disturbances often create their own unique set of fuelbeds that are usually named for the disturbance that created them. *Activity* fuels are those fuelbeds that have been altered by mechanical treatments, such as thinning, timber harvest, and mastication (Hirsch et al. 1979; Fig. 1.3a). The cut or fallen woody fuel particles, such as limbed branches, destroyed tree seedlings, and abandoned tree tops, that are left on the ground after fuel treatments are often referred to as *slash* in activity fuels. *Blowdown* fuelbeds are created by localized high-wind events that topple trees en masse (Woodall and Nagel 2007), while *hurricane* fuelbeds are caused by regional storm events (Busing et al. 2009; Fig. 1.3b). Insect and disease outbreaks often create fuelbeds that many consider hazardous (Jenkins et al.

Fig. 1.3 Examples of various fuelbeds named for the disturbances or vegetation that created them: **a** activity fuelbed (fuel treatment unit in northwestern Montana, USA), **b** hurricane (Shortleaf Pine, Texas USA; courtesy of the Fire and Environmental Rsearch Team, US Forest Service), **c** mountain pine beetle (lodgepole pine central Idaho), and **d** maquis fuel (Sardinia, Italy; photo courtesy of Valentina Bacciu)

2008). Mountain pine beetles, for example, alter both canopy and surface fuels, by killing pines and facilitating canopy growth of surviving competitors (Chap. 6; Fig. 1.3c). However, most fuelbeds are named for those vegetation types that created them; shrub fuel complexes, for example, are sometimes called brush, scrub, maquis, heathlands, and chaparral fuelbeds, depending on the geographical area (Dimitrakopoulos 2002; Keeley et al. 2008; Fig. 1.3d, Chap. 3).

1.2.3 Wildland Fire

Several fire science terms must also be defined to avoid ambiguity when describing fuels (Chap. 2). *Fire behavior* is a general term used to describe physical aspects of the combustion process such as speed and direction of fire spread. Other definitions of fire behavior include “the manner in which fire interacts with topography, fuels, and weather” (NWCG 2006). *Fire spread* is how fast a fire moves in a given direction, while *fire growth* is how large the fire gets in an area over time. *Fire intensity* is the combustion energy released from the burning of organic matter during a fire and is usually described using different metrics, such as reaction intensity, fireline intensity, and radiant energy (Keeley 2009). Fuel types that foster rapid fire spread (fine, flashy fuels) are quite different from those that create hot, intense fires (logs, deep duff, canopy foliage). *Fire effects* are the physical, biological, and ecological impacts of fire on the environment; *fire ecology* is the study of those impacts on living organisms and their environment; and the term *fire severity* is often used to describe the magnitude of fire impacts on the ecosystem (Morgan et al. 2014). *Fire danger* is a term used to describe the combination of both constant and variable factors on fire behavior, such as fuels, weather, and topography, which affect the initiation, spread, and difficulty of control of wildfires.

Wildland fires are usually divided into three types based on the fuel layer in which they are burning. A *crown* fire is the combustion of the canopy fuels above the surface fuel layer, and similarly, a *surface* fire is a fire burning the surface fuels (Chap. 2). A *ground* fire slowly burns the duff and soil organic matter through smoldering combustion. Most wildland fires have all three of these fire types at the same time.

Fires are also described in terms of their effects (Morgan et al. 2014). A *nonlethal surface fire* burns in the surface fuel layer and usually doesn't kill the majority of plants (<20 % mortality), while a *lethal surface fire* results in high plant mortality. A *stand-replacement fire* kills most plants, especially trees in the burned area (>70 % tree mortality; Agee 1993; Morgan et al. 2001). In *mixed severity fires* that contain evidence of the gradient between the other two types of fires distributed across space (Arno et al. 2000).

1.2.4 Modeling

Most fuelbed characteristics are described in terms of input requirements of the fire models that predict fire behavior and effects, so it is important to know the differences between model designs and approaches. This terminology is more descriptive than categorical so it is possible that models can be described by combinations of these terms. An *empirical* model is one that is based on observation and experiment and not on theory. Empiricism forms the basis for much of current fire and fuels research and generally provides the reference against which theory is tested (Sullivan 2009b). Empirical models are often composed of statistical correlations using data measured in the field or derived from laboratory experiments. Some use the term *phenomenological models* when taking a statistical modeling approach because they use information about how a system has typically behaved in the past to develop predictive equations and algorithms; the outcome of the process is predicted using surrogates for the causal mechanisms. Others use the term *statistical* models to indicate that statistics were used to develop the empirical model.

Theoretical models are generated from physical laws, such as those that govern fluid mechanics, combustion and heat transfer. Validation of these kinds of models is extremely difficult, although they may be extrapolated to a wide variety of fire situations. These models may also be called *mechanistic* or *process* models because they take a reductionist approach by explicitly representing the mechanisms that lead from cause to effect. For example, tree growth may be simulated using the ecophysiological processes of photosynthesis and respiration in a mechanistic approach. *Semiempirical* or *quasi-empirical* models are terms used for models that were developed using theoretical equations, but these equations were parameterized using empirical techniques (Sullivan 2009b).

Four key modeling terms are important tasks in fire simulations. *Initialization* is the process of inputting initial parameters into the model. These starting conditions are usually the quantification of fuel properties, such as loading and moisture. *Parameterization* is a term used to describe how the parameters in various equations and algorithms in the model are quantified. Some fuel attributes, such as mineral content, are not dynamic variables that users can input into fire models, but instead they are static parameters that the user cannot modify so it is important to know how these parameters were estimated. Statistical techniques are used for most parameter quantification, but some parameters in theoretical or physical equations can be estimated from the literature. *Calibration* is a term used to describe the adjustment of model inputs and parameters to achieve realistic results. There is always error in the quantification of both parameters and initial conditions in most models, and this error is often reduced by adjusting parameters or inputs so that subsequent simulations produce believable results. And last, *validation* is the process of describing the accuracy and precision of model results. Validation relies on comprehensive databases to use as reference for comparison against simulation results. Every modeling project should involve each of these four phases.

1.3 An Abridged History of Wildland Fuel Science

To fully understand why wildland fuels are described and defined the way there are today, it is important to trace the history of the application of fuels in fire management. Historically, most fuelbeds were described using terms that related more to fire behavior than ecology. Starting in 1919, Show and Kotok (1930) correlated fire behavior and firefighting descriptors to vegetation cover types to represent fuels, and called categories in this classification "hour control zones," which represented the time it took for a suppression force to arrive after an ignition. Hornby (1935) described fuels of the northern Rockies as categories in an ordinal fire behavior classification that integrated resistance to spread and suppression effectiveness levels. This approach was then employed to describe and map fuels for many other areas of the USA including the mid-west (Jemison and Keetch 1942), the mountains and seaboard of the Atlantic region (Banks and Frayer 1966), the Pacific Northwest (Abell 1937), and parts of New Jersey (New Jersey Department of Conservation and Development and US Department of Agriculture 1942). Both Barrows (1951) and Banks and Frayer (1966) revised the Hornby (1936) methods to include a fuel classification key that integrated fire behavior categories with vegetation and structural characteristics. Matthews (1937) even developed a plot-based sampling method to sample these fire behavior categories to describe fuel at finer scales. These fuel classification and mapping efforts had many problems, mostly because they described fire behavior not fuels. Brown and Davis (1973) recognized several other reasons why fuel descriptions based on fire behavior were ineffective: (1) expensive (costly to train and implement), (2) lack of detail (too broad to be applied locally), (3) obsolescence (mapped fuel types rapidly changed over a short time), (4) narrowly focused (evaluated for worst case burning conditions and envisioned the area burning in only large fires), (5) limited application (could not be used for other fire management tasks), and most importantly, (6) no associated comprehensive technique for measuring fuels.

Another historical approach often used for assessing fuels involved naming and describing fuelbeds based on vegetation characteristics. Mitchell (1929), for example, described the unique fuels of the mid-western USA using vegetation types. Fuel types in New Jersey, USA, were named after forest vegetation types for fire danger prediction (Little 1945). The basis of the Show and Kotok (1930) fuel descriptions was broadly defined vegetation types. Barrows (1951) stratified fire occurrence statistics by two vegetation-based fuel types (timber and grass), three management activity types (cutover, burned, forested), and several forest types in his description of wildfires in the US northern Rocky Mountains. Wendel et al. (1962) sampled fuel weights for various vegetation types in southeastern USA and then used the fuel weights to assign potential fire behavior ratings. Fuel classification systems for Ontario and New Brunswick, Canada, were based on vegetation characteristics (Walker 1971).

Both of these historical approaches ignored the inherent complexity of a fuelbed and attempted to simplify fuelbed descriptions into something that could be easily understood by managers. It was much easier to relate a fuelbed to a recognizable vegetation type or to some abstract interpretation of fire behavior than directly quantify the diverse array of fuel types in a fuelbed. The main reason for this was simple; there really wasn't any reason to stratify the fuelbed into its components. It wasn't until analytical tools, methods, and models were developed for fire management that there became a reason for dissecting fuelbeds into components and describing component properties.

The prediction of fire danger was the first concerted effort at creating a fire management tool (Hardy and Hardy 2007). Gisborne (1936), for example, differentiated fuel types in the fuelbed to more accurately estimate fuel moisture to predict fire danger and Curry and Fons (1938) differentiated fuel types to predict fire spread for fire danger. Fahnestock (1970) developed one of the first comprehensive fuel assessment methods that described the fuelbed as a complex of integrated fuel types. He used various fuel type properties, such as size, shape, and continuity, of three different fuel layers (ground, surface, crown) to rate the potential for spread and crowning. In the 1960s and 1970s, fire scientists around the world started creating fire behavior models that were then implemented into a variety of fire behavior prediction systems for managers. These systems required users to input specific fuel information by component and property (Rothermel 1972; McArthur 1966). Fire managers now had a quantitative description of a fuelbed that had a direct application—the simulation of fire behavior and effects. While there have been many modifications to fuel descriptions since 1960, wildland fuelbeds have mostly been described using a suite of components and properties that were specifically engineered for fire behavior computations.

The main problem with this engineering approach is that it is often incompatible with describing the dynamic ecology of wildland fuelbeds. Woody fuels, for example, may be defined by particle diameter classes with ranges that are so broad that the variability of biomass estimates within a diameter class may overwhelm differences across fuelbeds. Rates of decomposition and deposition of woody fuel particles may also vary greatly over the diameters of particles within one class. And because fire behavior-engineered components often tend to have high variabilities in the properties that are used to define them, it may be more difficult to quantify and evaluate important fire management concerns, such as fuel treatment longevity and effectiveness. Additionally, it may be more difficult to get accurate estimates of other fire-related management issues, such as smoke emissions, tree mortality, and fuel consumption, when high variability is a result of inappropriate fuel descriptions. Because wildland fuel science now has a much broader application than just fire behavior, such as fire effects, wildlife habitat assessment, carbon inventory, and tree regeneration potential, it may be time to take a more ecological approach to studying fuels.

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