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Chapter 2:

Fire Behavior and Effects: Principles for Archaeologists

Fire is a natural component of earth's ecosystems. Fire has impacted most landscapes of the Americas, having left evidence of its passing in trees, soils, fossils, and cultural artifacts (Andreae 1991; Benton and Reardon 2006; Biswell 1989; Bowman and others 2009; Boyd and others 2005; Cochrane and others 1999; DeBano and others 1998; Jurney and others 2004; Kilgore and Taylor 1979; Moore 1972; Nevle and Bird 2008; Pausas and Keeley 2009; Scott 2000, 2009; Swetnam and Anderson 2008; Swetnam and Betancourt 1990, 1998). Fires burn throughout a range of intensities from smoldering flameless fires producing little if any smoke to creeping fires with short, thin flames to raging crown fires with walls of flames 50 meters (164 feet) high, or more. The duration of a fire's passing may be as short as tens-of-seconds in the case of a fast moving surface or crown fire or as long as a day in smoldering ground fire. As fires burn throughout this range of intensities and durations the impact on the environment and the cultural resources therein varies tremendously.

Wildland fire behavior is highly varied due to such factors as the type of vegetation/fuel and its moisture content, atmospheric humidity, wind speed, and terrain. The spread and behavior of each fire is fairly unique, which can make fire seem both mysterious and unpredictable at times. However, the process is a fairly well understood phenomenon. Wildland fire is predictable in so far as both the current and antecedent weather conditions are reasonably well known. The state of the pre-burn fuels and weather are highly variable both spatially and temporally. The largest source of variation in fire behavior is local variation in the vegetation/fuel distribution (Ryan 2002; Turner and others 1999). It is this variability that most limits our ability to predict a fire's effects on cultural resources. This is why it is desirable to have local fuels and weather data when planning, implementing, monitoring and reconstructing a fire. In the case of wildfire, pre-burn conditions often must be inferred from post-fire proxy data, for example inferring preburn conditions from those in a "similar" near-by unburned area. Predicting fire behavior and understanding its effects requires knowledge of the fire environment, heat transfer principles, the responses of various artifact materials to heat, and to a lesser extent, the chemicals released by fire (such as ash or smoke) or used in fire suppression (such as retardants or foams). Models exist to predict fire behavior and its effects through interpreting weather and fuel conditions. It is important for managers to recognize that some factors cannot be controlled; there will always be spatial variation, adverse environmental conditions, and complex vegetative structures that make prescription development an inexact science. As we gain a better understanding of the effects of fire on cultural resources, we must take appropriate action to reduce and manage risk to these assets.

The fire science literature includes a broad spectrum of interrelated topics. Terminology within the field varies in part because of the varying space and time scales. For example, spatial scales vary from individual fuel particles to landscapes, and time scales vary from fire residence times measured in seconds to fire return intervals measured in years to fire regimes measured in centuries, depending on the author's subject matter. Numerous previous authors have described fire processes at multiple scales from combustion fundamentals to broad-scale ecological interpretations. The reader interested in more fully understanding the field of wildland fire science is referred to those texts (see Agee 1993; Chandler and others 1983a,b; DeBano and others 1998; Gill and others 1981; Johnson and Myanishi 2001; Omi 2005; Pyne and others 1996; Sugihara and others 2006; Wright and Bailey 1982).

The purpose of this chapter is to provide cultural resource specialists with a primer on fuels and fire to enable them to work more effectively with fire managers in developing fuel treatment and restoration plans, managing wildfires, and conducting post-fire rehabilitation. This chapter provides a scientific foundation for predicting the potential impacts of fire on cultural resources. It also defines terms and concepts and identifies their practical implications to cultural resources. Prescribed fire and wildfire conditions associated with damage to cultural resources are discussed, as are ways to integrate planning measures to mitigate fire's effects on cultural resources.

Fire Basics

To either predict or assess the effects of fire on cultural resources, it is necessary to understand a few basic fire concepts. There are three essential conditions that must be present for a fire to ignite and continue burning; these three factors comprise the "fire triangle" (fig. 2-1 bottom left). There must be fuel to burn, a supply of oxygen to support combustion, and sufficient heat to cause successive ignition of fuel particles. Without all three components, fire cannot exist. Indeed, fire suppression tactics rely on this fundamental principle and design suppression strategies to either remove fuel (for example fireline construction and burnout), remove oxygen (for example to smother with dirt or foam) or reduce heat (for example to quench with water or retardants).

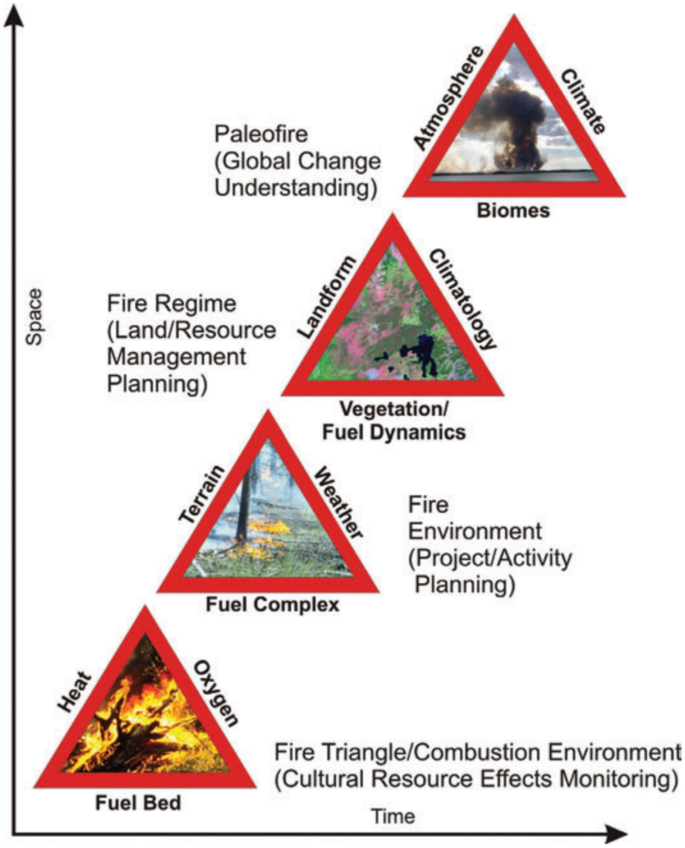

Figure 2-1—The multiple scales of fire (adapted from Scott 2000; Reinhardt and others 2001; Moritz and others 2005; Cochrane and Ryan 2009).

Fire affects biophysical processes across multiple temporal and spatial scales from micro-scale phenomenon (e.g., an effect on an individual plant or single cultural resource) to broad landscape patterns and processes. The "fire triangle" (fig. 2-1 lower left) is appropriate at the combustion scale, a small localized area where fuels making up the fuel bed are relatively homogeneous. The "fire environment scale" (fig. 2-1 second from bottom) is appropriate at the scale at which fuels treatment and restoration projects are planned and implemented. The "fire regime scale" (fig. 2-1 second from top) is appropriate for describing the role of fire in shaping ecosystem structure and function. Archaeologists, paleontologists, and those who study human development and migration often consider a higher, paleo-fire scale (Rickards 2010; Ruddiman 2003, 2007; Scott 2000, 2009) (fig. 2-1 upper right) (adapted from Cochrane and Ryan 2009; Moritz and others 2005; Reinhardt and others 2001; Scott 2000).

Combustion

Combustion is a physical process involving the rapid oxidation of fuels releasing carbon dioxide, water, mineral ash (e.g., Ca, Mg, K) and numerous other compounds, the chemistry of which varies with the type of fuel burning and the efficiency of combustion. The rapid oxidation of fuels also produces detectable heat and light.

Combustion is divided into four phases: preheating (or preignition), flaming, smoldering, and glowing (DiNenno and others 1995; Grishin 1997; Pyne and others 1996; Williams 1982). The fire's phase is dependent on the nature and condition of the fuel and oxygen availability. Wildland vegetation burns by turbulent diffusion flames in successive interactions between combustion gases and unburned fuel. Energy released by combustion of gases is absorbed by solid fuel particles in the preheating or first phase of combustion.

Preheating is an endothermic or energy absorbing phase. As the flame front approaches a fuel particle its temperature increases, gradually at first, then more rapidly. At about 100 °C (212 °F), free water begins to rapidly boil leaving an outer shell of dry fuel (table 2-1). The amount of energy needed to vaporize water contained in the fuel increases with the moisture content of the fuel. In the case of live, actively growing fuels the moisture content may be quite high (100 to 200 percent on an oven dry basis). As the particle continues to absorb heat, bound water and low molecular weight volatile compounds (such as waxes, terpenes, and resins) vaporize, and decomposition (pyrolysis) of solid fuel (principally composed of cellulose) begins. If the decomposition rate is fast enough to form a combustible mixture of vapors (carbonaceous gases), flaming combustion results.

Flaming combustion, the second phase where nearly all destructive fires occur (DeHaan 1997; Williams 1982), is an exothermic process. Flaming involves the combustion of gases (gas-phase) evolved from the preheating of the solid fuel. This energy is critical to the preheating of adjacent fuel particles and sustaining the chain reaction. In wildland fuels where oxygen is not usually limiting, fuel particles burst into flame at around 325 °C to 350 °C (617 °F to 662 °F) (ignition temperature) with a rapid rise in the local temperature. During the flaming phase, luminescent flames are produced as a flame envelope develops above the solid fuel. Theoretically, temperatures are much higher, 1800 °C to 2200 °C (3272 °F to 3992°F) where chemical bonds are being broken and flames can't exist below around 1300 °C (2372 °F) (Satio 2001). However, as the flame envelope includes many products of incomplete combustion, noncombustible particles, and cooler air entrained into the combustion zone from the surrounding area, measured flame temperatures are usually between 500 °C and 1000 °C (932 °F and 1832 °F) (Butler and others 2004; DeBano and others 1998; Pyne and others 1996; Sullivan and others 2003). Solid fuels burn at high temperatures, distilling volatile substances while creating charcoal. To continue to burn, fuels must continue to produce energy faster than it is lost to the surrounding environment. When the energy release rate drops before all volatiles have been liberated, flames become discontinuous and the fire transitions into the smoldering phase (Bertschi and others 2003).

Table 2-1—Temperatures associated with phases of combustion.

Temperature °C	Effect
0-100	Preheating of fuel: free water is evaporated
100-200	Preheating of fuel: bound water and low molecular weight compounds volatilized, decomposition of cellulose (pyrolysis) begins, solid fuel is converted into gaseous vapors
200-300	Preheating of fuel: thermal degradation continues more rapidly
300-325	Ignition temperature in well aerated wildland fuels: transition to flaming
325-400	Flaming phase: rapid increase in decomposition of solid fuel
400-500	Flaming phase: gas production rate peaks around 400 °C and declines between 450 °C and 500 °C as all residual volatile compounds are released.
500-1000	Flaming phase: Maximum flame temperatures within flames may approach 1600 °C in deep flame envelops but temperatures of 500 °C to 1000 °C are more typical.
500-800	Glowing phase: residual carbonaceous fuel (charcoal) burns by glowing combustion. The combustion of charcoal is associated with the liberation of CO and CO_2

Smoldering combustion is often characterized by a complex suite of carbon-rich compounds produced by incomplete combustion including large amounts of hydrocarbon-rich (e.g., tars) smoke (Bertschi and others 2003; Urbanski and others 2009; Yokleson and others 1997). Smoldering fire often occurs when oxygen depletes during flaming combustion. The fire still emits high temperatures but produces no visible flame. Once the entire fuel particle has been heated to around 500 °C (932 °F) the volatile compounds necessary to support flaming (gas-phase) combustion have been exhausted, smoke ceases to rise from the charcoal, and the remaining charcoal burns by **glowing** (solid-phase) combustion. This phase continues until either all the fuel becomes non-combustible ash and the fire goes out, or until the fuel is quenched or cooled leaving charcoal residues. Until the latter cool-down stage of a fire, flaming and smoldering occur simultaneously to some degree as evidenced by the flickering flames of a dying campfire, for example.

Fires vary in their combustion efficiency. Combustion efficiency is the ratio of heat released to the maximum heat that could be released in complete combustion in a well ventilated dry environment (Urbanski and others 2008; Ward 2001). This is a function of the fuel's chemistry, principally its moisture content and the fuel bed packing ratio, which affects the flow of air to the combustion zone. The packing ratio is the proportion of the fuel bed volume that contains fuel particles (fuel volume + air volume = total fuel bed volume). It is a measure of how tightly fuels are packed together, which affects air flow into the fuel bed during combustion. To illustrate the influence of packing ratio, consider the spatial distribution of needles in a conifer tree vs. those same needles compacted in the forest floor duff after a number of years on the ground. The former burns rapidly and efficiently by flaming combustion whereas the latter burns slowly and inefficiently by smoldering combustion. Combustion efficiencies range from as high as 95 percent to as low as 50 percent (Grishin 1997; Pyne and others 1996; Urbanski and others 2009). Flaming, the second phase, which is gaseous combustion, is the most efficient. Products of incomplete combustion include carbon monoxide, nitrous oxides, sulfurous oxides, hydrocarbons, and solids (soot). The darker the smoke, the more unburned carbon particles (soot) are present and the lower the combustion efficiency (Bytnerowicz and others 2008; Urbanski and others 2009). Light colored smoke indicates more complete combustion of fuel elements, lower production of soot and, therefore, higher combustion efficiency. If pyrolysis occurs in the absence of oxygen, such as may occur in buried wood or organic artifacts, destructive distillation occurs at higher temperatures (600 °C (1112 °F)).

Heat Transfer

The three primary mechanisms of heat transfer are radiation, convection, and conduction. All bodies emit radiant energy as a function of their surface temperature. **Radiation** is the flow of electromagnetic energy through space at the speed of light. The radiant energy received at the surface of a body (for example, a fuel element, artifact, or rock art) decreases rapidly with distance from the heat source or flame and increases rapidly as the temperature of the emitting source increases (that is, as fire intensity increases as exhibited by the size or temperature of the flames) (sidebar 2-1) (Butler and others 2004; Pyne and others 1996; Sullivan and others 2003). The emissivity of a flame increases with the depth of flaming zone and approaches unity (i.e., the maximum possible for a black body emitter at around 1 meter (3.28 feet) (Butler 1993; Butler and others 2004). The actual distance depends somewhat on the efficiency of combustion. Beyond this distance deeper flame zone depths do not emit more radiation. Deeper flame zone depths are, however, associated with taller flames that can heat bodies at somewhat greater distances. Larger flames also are associated with greater convective heat transport.

Sidebar 2-1—Impact of Flames on Rock Art

Cultural resources may be directly or indirectly impacted by the passage of a wildland fire. Direct or first order impacts include the effects of heat (fig. S1.1); the deposition of combustion products (e.g., tars, soot and ash); and the exposure of cultural resources to discovery. The latter may lead to increased vandalism. Cultural resources may also be indirectly impacted by fires. Indirect or second order effects include the destruction or redistribution of artifacts due to accelerated erosion of the burned site. Of the direct impacts, the effects of exposure to high heat are the most critical concern. Elevated temperature during wildland fire is the issue of greatest concern. Above ground cultural resources may be bathed in flames where they are exposed to both high convective and radiant heating (fig. S1.2). Resources may be exposed to the smoke and hot gasses above the flames where convective heating is the dominant source of damage. The potential for damage increases with the intensity or energy release rate of the fire as is visually apparent by larger flames. The distance at which damage can occur increases with the size of the flames (fig. S1.3).

Figure S1.1. Spalling of rock art following the 2003 Hammond Fire, Manti LaSal NF, Utah (Johnson 2004). Pictograph damaged by heat from forest fire (photo Clay Johnson, Ashley NF).

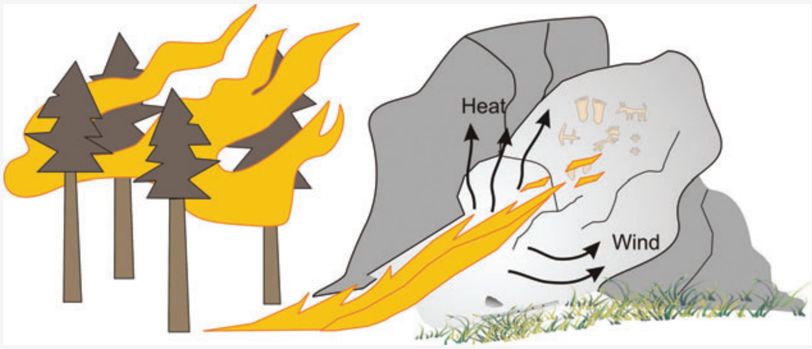

Figure S1.2. Convective and radiant heat from fires are a major source of damage to above ground cultural resources such as rock art.

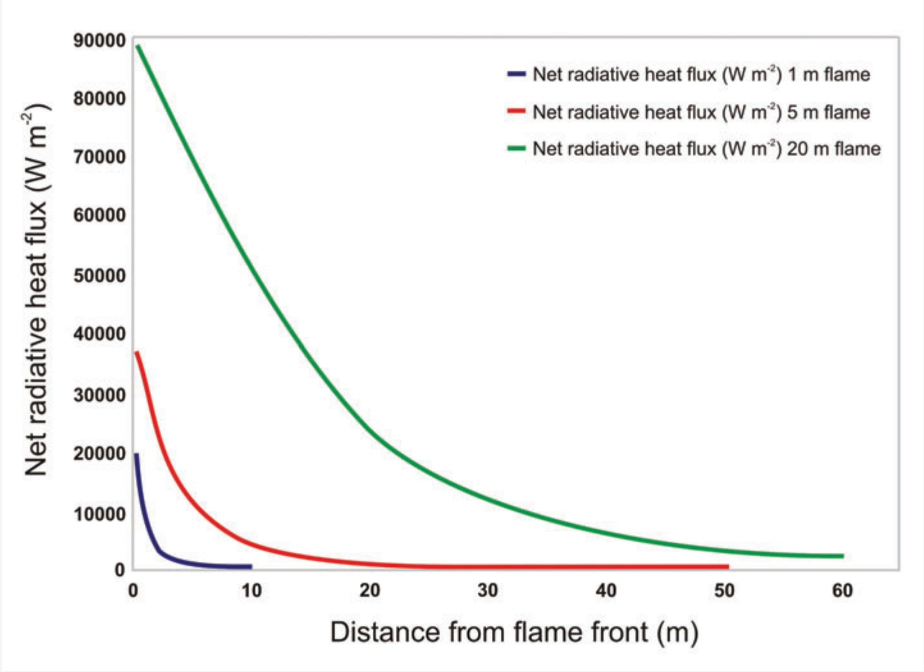

Figure S1.3. Radiant heat flux received by a rock surface or a log cabin wall decreases with distance from the flame envelope and increases with the size of the flame envelope. The more intense the fire, as exhibited by the larger the flame, the greater the distance that damage can occur.

Convection is the transfer of energy within liquids and gases from a heat source (flame) to a cooler area by transport of energy in the form of heated molecules. In contrast to the typical lay use of a fluid as describing a liquid, gasses behave as fluids in a physics and engineering context, that is gasses flow from places of high temperature towards places of lower temperature. Convective heat transport is a result of the fluid motion of gases and particulates (Cheney and Sullivan 2008; Cochrane and Ryan 2009; DeBano and others 1998; Pyne and others 1996; Van Wagtendonk 2006). Flame and billowing smoke above a wildland fire are the most visible examples of convective heat transport.

Radiation and convection can only heat the surface of an opaque substance (for example, fuels or artifacts). The heating of the interior of the substance occurs through conduction. **Conduction** is the transfer of energy through a substance by the direct imparting of heat from molecule to molecule without appreciable movement of molecules within the substance, which is extremely important for heat transfer within solids such as fuel particles. Likewise, conduction is critical for transferring heat to artifacts buried in the soil profile. The rate of heat movement within objects depends on the temperature gradient across the object and its thermal conductivity. Metals generally are great conductors but wood, forest litter, and air are poor.

Spatial and temporal variation in fire behavior, variations in the exposure of cultural materials, and the thermal properties of those materials all interact to influence how fire affects cultural resources. From a small fire that could be considered a point source, radiation decreases with the square of the distance. However, in wildland fires where flame fronts approximate two-dimensions (for example a line of surface fire burning through a fuel bed) or three-dimensions (for example a wall of flames from a crown fire) radiation decreases much more slowly with distance (sidebar 2-1). This helps explain, however, why two surfaces or surface artifacts in close proximity might experience different degrees of damage. If two nearby artifacts "see" significantly different flame emissivities owing to their particular viewing of the fire, they will be differentially affected. Most substances found in nature as well as most human-made materials consist of mixtures of compounds each with their own thermal properties. Differences in thermal conductivity and thermal expansion of various compounds within a material lead to variable heat transfer rates and internal stresses. These forces can cause structural failure such as exfoliation or spalling of rock (lithic) materials, fracturing of ceramic artifacts, and shattering of glass. Because soils are porous, multiple heat transfer mechanisms occur simultaneously in soils, but conduction dominates, particularly after moisture has been driven off at around 100 °C (212 °F) (Albini and others 1996; Campbell and others 1994, 1995; Massman and others 2010).

Under suitably severe conditions, fire may spread beyond a fire's perimeter by spotting, the lofting and transporting of burning embers or sparks through the convection column and wind thereby initiating new fires up to 1 km (0.6 mi.) or more (Albini 1981b, 1983). This fourth mechanism, a special case of convective heat transfer, is referred to as mass transport and is of particular concern to the protection of organic cultural resources—for example, cabins—at some distance from a fire (see chapter 9).

The practical significance of heat transfer mechanisms to cultural resources will be discussed in subsequent sections.

Fire Behavior Principles

Fires in wildland fuels are predominantly free burning, that is they expand or propagate by successive ignition of fuel elements along their perimeter. Figure 2-2 illustrates combustion zones and flame characteristics commonly found in the fire science literature. Prior to ignition, fuels must be raised to ignition temperature. Fuels ahead of the spreading fire are preheated by radiation and convection (fig. 2-2a). The radiative power of the flame approaches unity, the theoretical maximum, as the depth of the flame zone approaches 1 m (3.28 feet) as illustrated by yellow in the flame. Radiation from deeper flames, as illustrated in red, no longer contributes to preheating of fuels ahead of the fire. Energy from larger flames does contribute to increased turbulence and convective heat transport thereby increasing the likelihood and effectiveness of flame contact with unburned fuels ahead of the fire as well as the lofting of embers. Flames typically pulsate with the local wind and the flame tilt angle varies, periodically bathing fuels ahead of the fire in flames. Thus both radiation and convection are important for preheating and igniting fuels ahead of the fire. Flame zone temperatures are variable depending on the rate of spread and type of fuel burned but are typically in the 325 °C to 800 °C (617 °F to 1472 °F) range. The deeper the flame zone, the higher the temperature. Where the human eye sees the visible flame tip depends somewhat on local lighting conditions. Flame tip temperatures are in the 500 °C to 600 °C (932 °F to 1112 °F) range. Flame length is the best visual indicator of the fire's energy release rate (fig. 2-2b). The depth of burn is illustrated by the reduced thickness in the fuel bed plane with the passage of the fire (fig. 2-2a,b). Flames at the head of an advancing fire lean into unburnt fuel preheating it. Fireline intensity, as manifested in the length of flames as well as the flame zone depth (fig. 2-2), is at its maximum at this location on the perimeter (Cheney and Sullivan 2008) (fig. 2-3).

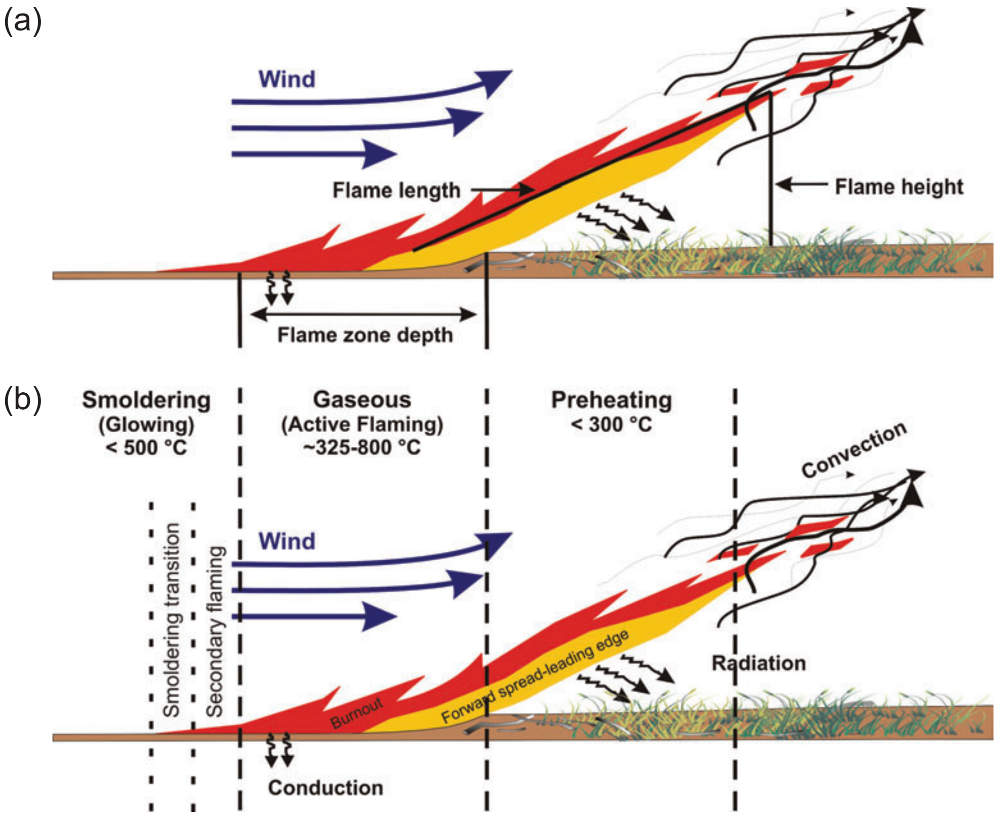

Figure 2-2—Stylized flame zone characteristics (a), combustion phases, and dominant heat transfer mechanism (b) (adapted from Rothermel 1972; Pyne and others 1996; Cochrane and Ryan 2009).

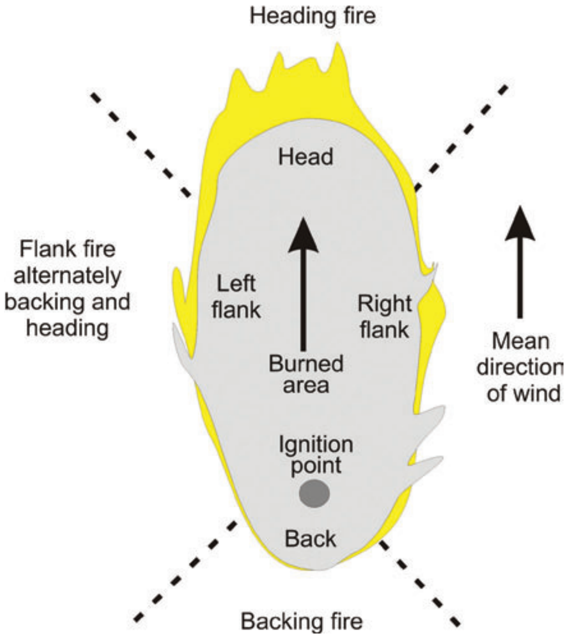

Figure 2-3—The parts of a moving fire (from Cheney and Sullivan 2008).

Here heat transfer by radiation and convection are also at their maximum. Likewise, the potential for lofting burning embers and downwind spotting is maximized at the head of a fire's perimeter (fig. 2-3). At the rear of the fire, where the fire is backing either into the wind or down-slope, flame length is at its minimum and flames typically lean over the burned fuel, reinforcing the smoldering phase. The flame zone depth is also at its minimum but, particularly in fine surface fuels, the slower advance of the fire (termed spread rate) is also associated with more complete burnout and greater duration of surface heating (Cheney 1981; Cheney and Sullivan 2008). On the flank, the fireline intensity and flame length are intermediate. Flames may lean either over the unburned fuel or the burned fuel depending on local variations of in-drafts or wind. The effect can often be seen in char marks on tree trunks or physical structures, which indicate the direction of wind at that point in time when a fire passed. It is common to find char marks that indicate local winds at right angles to the prevailing spread direction. Fires often pulsate, surging forward at several areas along the fire's perimeter, and fireline intensity increases where adjacent flanks of the fire converge. Thus, there can be considerable variation in fire behavior and effects even within relatively homogeneous fuels (Catchpole and others 1982, 1992; Cheney and Sullivan 2008; Finney 1998, 1999; Ryan 2002). Fire intensity, flame size, and temperatures within a fire generally vary within a fire's perimeter. Head fires are more intense overall but backfires can be more effective at heating the ground surface (Fahnestock and Hare 1964; Hare 1961; Lindenmuth and Byram 1948; Martin and Davis 1960; Stinson and Wright 1969; Trollope 1978). For example, in light surface fuels Lindenmuth and Byram (1948) found head-fires were hotter at heights above 0.5 meters (~18 inches) whereas backing-fires were hotter below 0.5 meters (~18 inches).

There are numerous decision support tools that enable managers to predict and manage fire behavior and effects whether in planning fuels treatment or restoration projects or suppressing and rehabilitating wildland fires. The succeeding sections provide cultural resource specialists with additional knowledge and background necessary to work effectively with fire managers in order to predict and manage fire effects on cultural resources. Principles and models commonly used by fire managers in the United States and Canada are described.

The Many Scales of Fire

The characteristics of fire vary within individual fires as fuel and environmental conditions vary in time and space (fig. 2-1). Fire concepts change across spatial and temporal scales. At the finest scale, individual fuel beds ignite, burn, and transfer energy to their surroundings at the combustion scale. This is the scale of the fire triangle familiar to all fire fighters. At this scale, heat, oxygen, and fuel are the important elements. At this microsite scale, combustion events range on the order of several seconds for the passage of a flaming front to a few days in the case of smoldering peat fires. Their effects are monitored at the small sample plot or quadrat scale. The next higher scale is the scale of the fire environment. The fire environment is the summation of all the combustion environments within an individual fire. At this scale, fire behavior monitoring and modeling are used to evaluate fire as fuels, heat, and oxygen vary with terrain and weather within individual fires. Temporal variations of individual fires range from hours to days as fires spread across landscape-scale land areas. Their effects are assessed by stand and community-level surveys. At the next higher spatial and temporal scale, fire regime concepts describe the modal fire type that occurs at stand/community, landscape, and biome levels across decadal to century-long time-scales. At these scales, broad class descriptors of impacts on major processes are inferred from dendroecological and paleoecological techniques. At the fire regime scale, fire characteristics vary between successive fires on the same site as the time since, and severity of, the last disturbance varies. Site productivity, disturbance history, periodic weather anomalies (such as drought), and variations in climate cycles all contribute to fire's variability in time and space (Clark 1989; Clark and Royall 1995; Kitzberger and others 2007; Morgan and others 2001; Power and others 2008; Swetnam and Betancourt 1990).

Fire affects societies and natural biophysical processes in numerous ways. As such, it has attracted scientists from fields ranging from combustion science to ecology, hydrology, geosciences, anthropology, and archaeology. At the combustion science scale, the physics and chemistry of fuels and heat transfer mechanisms predominate in the study of small scale fire phenomenon on the order of seconds to minutes. This is the fundamental scale at which fires burn. It is at this scale that investigators study stationary fires and their impacts on organisms and individual cultural resources. At the fire behavior scale, the spatial and temporal variability in fuels, weather, and terrain dominate in the evaluation of fire potential within and between stands and across landscapes on the order of hours to weeks. This is the scale at which actively spreading individual fires are studied and their effects understood on multiple processes (for example plant community dynamics, erosion, or hydrologic effects). This is also the scale at which most fire management projects occur. At the even higher scale of land management planning, managers are concerned with broad-brush differences in fuels and fire potential for large planning areas on the order of multiple seasons to centuries. At these spatial and temporal scales, scientists synthesize patterns of fire occurrence to better understand the relationship of fire to numerous ecosystem properties that occur on the order of years to centuries. This scale of wildland fire science is the fire regime scale (fig. 2-1). Above the fire regime scale is the paleo-fire scale. Understanding fire at this longer scale is important for understanding climate-vegetation-human interactions (Boyd and others 2005; Pausas and Keeley 2009; Power and others 2008). There is some interaction between scales. Insights from one scale inform our understanding of fire phenomenon at the next higher scale. For example, conceptually, fuel particles aggregate up to make fuel beds and fuel beds aggregate up to make fuel complexes necessary for predicting behavior of individual fires.

As each discipline has studied fire phenomena, they've focused on their particular disciplinary aspect of fire and each has developed their own concepts, terms, and sets of measures. As one describes fire at finer scales, terms and illustrations are based on precisely measured biophysical parameters that typically require specialized instrumentation (such as, fireline intensity and heat transfer mechanisms). As one describes fire at successively broader temporal and spatial scales, illustrations rely more on broad concepts and general trends and tendencies based on outcomes (for example, fire periodicity and severity) and less on the physics and chemistry of specific fire events (fig. 2-1). The use of similar terms developed by specialists who are focused on one discipline or scale vs. another leads to confusion, which can be particularly difficult for professionals from quite dissimilar disciplines such as cultural resources. It is, however, important to consider the purpose for which an investigation was conducted, or a model constructed, when applying concepts and models to fire and cultural resource problems.

Fire Behavior and Effects: Concepts and Models

Fire Environment

An essential element of wildland fire is the biophysical fire environment, which is composed of three factors: weather, terrain, and fuels. Each of these varies in both time and space (fig. 2-1). **Weather** is the state of the atmosphere surrounding the earth. The primary weather factors affecting wildland fire are temperature, wind speed, wind direction, humidity, precipitation, and sky condition (dark vs. cloudy vs. sunny). **Terrain** is the shape of a particular landform on the earth's surface and is often described by slope, aspect, elevation, and drainage properties. **Fuels** are fire's source of energy released in combustion. Fuels are comprised of living and dead biomass from the ground, the surface, and the canopy stratum and come in many shapes, sizes and varieties (fig. 2-4).

Fire managers have long recognized that weather conditions, terrain steepness, and the amount of available fuel have a dominant effect on a fire's energy release characteristics (Albini 1976; Grishin 1997; Pyne and others 1996; Rothermel 1972; Stocks and others 1989; Wotton and others 2009). Of more interest in bioconservation and restoration studies is the understanding that the energy released by fire has the potential to do ecological work, that is, to change a host of ecosystem state variables (Dickinson and Ryan 2010). Thus, quantification of the energetics of fires is desirable in ecological studies (Butler and Dickinson 2010; Johnson 1992; Johnson and Miyanishi 2001; Kremens and others 2010; Massman and others 2010). Likewise the energy released during a fire has the potential to directly impact cultural resources through the thermal effects on artifacts and the cultural landscape. However, fire behavior is highly variable in non-uniform fuels, instrumentation is costly, and it is often impractical to sample fire behavior except on small experimental plots, making it difficult to quantify the magnitude of fire treatments in ecological studies or restoration projects.

Weather—Weather generally refers to the day-to-day temperature, relative humidity, wind, cloudiness, and precipitation activity. Meteorology is the interdisciplinary scientific study of the atmosphere. It focuses on weather processes and forecasting. In contrast, climatology is the study of climate, which is scientifically defined as weather conditions averaged over a period of time. By convention the climate of an area is as the average weather for the preceding 30 years, but also includes data on extreme events. Climatology is an important consideration in the study of fire regimes (fig. 2-1). As the fire environment is concerned with the behavior of an individual fire on a specific site, fire weather is the meteorological process of concern for predicting and understanding fire behavior and effects.

Weather is a set of all atmospheric phenomena occurring at a given time. Weather phenomena occur in the lower atmosphere, the troposphere, an air layer varying from roughly 7 km (4.3 mi) thick in Polar Regions to 20 km (12 mi) thick in the tropics. The troposphere contains approximately 75 percent of the atmosphere's mass and 99 percent of its water vapor and aerosols. Weather patterns result from differences in atmospheric density caused by differences in temperature and moisture content of the atmosphere in one region of the globe versus another. Short term weather, hours to days, is most critical for determining the fire environment. However, longer term weather, seasonal patterns, and periodic wet or dry cycles (e.g., drought) have major effects on the moisture content

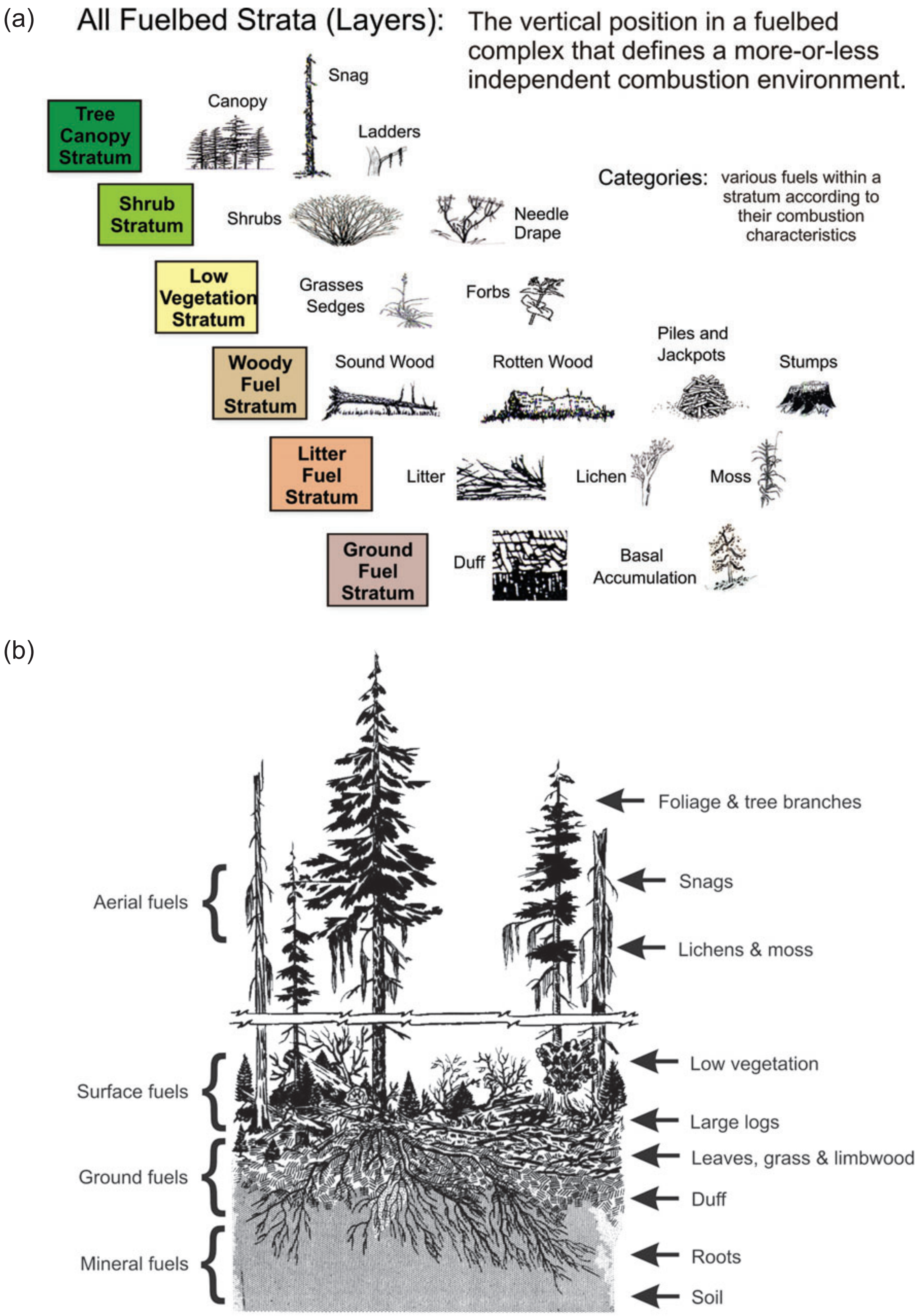

Figure 2-4—Fuel elements by stratum (a) (from Sandberg and others 2001) aggregate to make a fuel bed (b) (from Barrows 1951).

of large logs and duff (Deeming and others 1977; Van Wagner 1987) as well as live fuel moisture. These fuel moistures also affect the amount of available fuel and, therefore, the fire environment. Those readers interested in more details about fire weather are referred to the classic Fire Weather Handbook (Schroeder and Buck 1970) or subsequent fire science texts (see for example Chandler and others 1983a,b; Flannigan and Wotton 2001; Gill and others 1981; Lawson and Armitage 2008; Minnich 2006; Omi 2005; Pyne and others 1996).

Weather—specifically temperature, relative humidity, wind, and drought—defines the fraction of the total fuel that is available to be consumed in a given fire. The short-term weather history is the primary determinant of the flammability of the moss and lichen layers, loose litter, foliage, and fine twigs (Albini 1976; Stocks and others 1989; Wotton and others 2009). The moisture content of fine fuels is reflected in the U.S. National Fire Danger Rating System (NFDRS) 1- and 10-hour time-lag fuel moistures (Deeming and others 1977) and the Canadian Forest Fire Danger Rating System (CFFDRS) fine fuel moisture content (FFMC) (Stocks and others 1989; Van Wagner 1998; Wotton and others 2009). Long-term weather determines the moisture content and combustibility of deeper organic layers and dead logs. The moisture content of these fuels is reflected by the NFDRS 1,000-hour time-lag fuel moisture (Deeming and others 1977), Canadian Duff Moisture Code and Drought Code (Hirsch 1996; Stocks and others 1989; Van Wagner 1987, 1998; Wotton and others 2009), Keetch-Byram Drought Index (Burgan 1988, 1993; Fujioka and others 2008), or Palmer Drought Index. Wind is perhaps the single most important cause of spatial and temporal variation within boreal forests. Fires often pulsate between intense surface fires and crown fires with only modest changes in wind speed (Finney 1998; Scott 1998; Scott and Reinhardt 2001; Van Wagner 1977, 1993). The result is a mosaic of small crown fire patches instead of the large expanses that occur in sustained wind-driven fires.

Terrain—Terrain refers to the general relief or topography of an area. Terrain is the most constant factor in the fire environment. It strongly influences fuels and weather. The earth has been shaped through millennia by wind, water, and tectonic forces creating mountains, valleys, plains, and canyons. The resulting landforms affect the amount of solar radiation incident on a site, precipitation patterns, wind flow patterns, and evaporation, all of which affect the frequency duration of flammable periods and a site's ability to grow biomass. Slope steepness and aspect are important terrain features affecting the fire environment. Slope is measured as the increase or decrease in elevation over a fixed horizontal distance and is usually expressed as a percent. In the field, slope is typically measured over a distance of 30 meters (98 feet) or calculated from contour lines on a map. The steepness of a slope influences fire behavior through convective preheating fuels thereby increasing a fire's intensity and rate of spread. Because heat rises, fuels on steeper slopes above fires dry quickly and ignite faster than fuels on relatively flat slopes. The direction a slope is facing is called the aspect. Aspect is most commonly expressed as one of the four cardinal directions and their bisectors (e.g., N, NE, E, SE, etc.) and occasionally as the compass azimuth in degrees. The shape of the terrain influences wind speed and direction as solar radiation differentially heats the ground on varying aspects throughout the diurnal cycle. In addition to slope and aspect, elevation affects both the temperature and humidity of the air and, therefore, vegetation/fuels and fire potential. Slope also interacts with subsurface geology resulting in moist microsites (e.g., seeps and springs) that affect vegetation/fuels and fire potential. Gravity, through its influence on erosion and ground water, affects hill-slope hydrology (Neary and others 2005; Potts and others 1986; Swanson and others 1988; Wohlgemuth and others 2006) leading to spatial differences in soil water content. These microsite differences also directly affect surface and ground fuel moisture contents (Hatton and others 1988; Samran and others 1995).

The influence of terrain and landform on surface energy and water budgets follows physical laws and is, therefore, well known (Kunkle 2001; Schroeder and Buck 1970). However, due to the sparse coverage of weather stations, a lack of good spatial data on weather often leads to considerable uncertainty in predicted fire weather. This is particularly true for winds (Butler and others 2006). For fuels treatment and restoration planning, reasonably robust models are available for extrapolating weather and fuel moisture from weather stations to the fire environment (e.g., FireFamilyPlus http://www.firemodels.org/index.php/national-systems/firefamilyplus).

Fuels—Fuel is the burnable organic biomass on a site. Fuel is the source of energy that does the work of change, whether it is a change in the state of various ecosystem components or damage to a cultural resource. The most important aspect of fuels is to understand that fuels can ignite and burn only when a certain combination of conditions is met. These conditions are described in this section. Fire influences fuels in three ways. First, fire consumes fuel. Second, it creates fuel by killing vegetation. Third, it indirectly affects fuels by altering the site, thereby influencing post-fire vegetation dynamics, the resultant fuel complex, and the potential for future fires (Ryan 2002).

Wildland fuels are all chemically similar. Vegetative biomass fuels are of a class of chemicals called polymers consisting of cellulose (41-53%), hemicellulose (15-20%), and lignin (16-33%), with lesser amounts of secondary plant metabolites (for example fats, oils, waxes, resin), and minerals (calcium, potassium, magnesium, silica) (DeBano and others 1998; Grishin 1997; Pyne and others 1996; Ward 2001). Wildland fuels are described by their physical and chemical properties when modeling fire danger or potential fire behavior in the United States (Albini 1976; Andrews 2005; Deeming and others 1977; Rothermel 1972), but in Canada they are described by a vegetation-based physiognomic nomenclature (for example, dominant species composition and stand structure) (Hirsch 1996; Stocks and others 1989; Wotton and others 2009). Likewise, field ecology studies primarily rely on vegetative physiognomic characteristics to characterize fuels and fire potential.

At the finest scale, fuels are characterized by their physical and chemical properties as they affect combustion. More specifically, fuels are described by their particle size and chemical composition (for example, heat and moisture contents). For modeling purposes in the United States and elsewhere where the Rothermel (1972) model and its variants are used, the commonly recognized particle sizes are broken down based on the time-lag equilibrium moisture concept (Schroeder and Buck 1970) (table 2-2). Biomass fuels are hygroscopic, meaning that they absorb or lose moisture in response to changes in atmospheric moisture, which is generally defined in terms of the relative humidity (Deeming and others 1977; Nelson 2001; Schroeder and Buck 1970). As humidity rises or falls, so does fuel moisture. One time-lag is the time it takes for a fuel element to change approximately 63 percent from its initial moisture content to its new equilibrium following an atmospheric humidity change. The concept of equilibrium moisture content is valid for dead fuels over the range of about 2 percent up to the fiber saturation point of 30 to 35 percent, depending on the species characteristics and the degree of rottenness. Above this point, free water begins to form in intra- and inter-cellular spaces of the fuel. It takes approximately five time-lags for a fuel particle to come into equilibrium with the atmosphere. The atmosphere is not often stable for five time-lags so fuel moisture is almost constantly changing. Relative humidity changes throughout the day as the temperature rises and falls through its diurnal cycle. Relative humidity also changes when weather fronts bring in a new air mass to a site of interest. However, the time-lag concept is useful not only because it describes the direction of moisture change (drying or wetting) but also how fast fuels respond to weather changes. It is also related to how fast particles ignite and burn in wildland fires. For fire modeling purposes, the size class is expressed as a function of the surface-area-to-volume ratio (SAV, often represented by the Greek σ in U.S fire modeling literature). Commonly, downed woody debris in the 1-, 10-, and 100-hour time-lag classes (i.e. woody fuels less than 7.6 cm diameter (< 3.0 in.)) are referred to as fine woody debris (FWD) whereas logs greater than 7.6 cm diameter (> 3.0 in.) are referred to as coarse woody debris (CWD) (Sikkink and others 2009). CWD typically includes all logs both sound and rotten. The time-lag concept is a useful one for describing fuel properties but cannot be interpreted rigidly. Fine-fresh needles from conifer and schlerophoulos (i.e., waxy evergreen) broadleaved species have longer time-lag responses than weathered needles and non-schleroph†olous species (e.g., pine needles) (Anderson and others 1978). Lags larger than 20 cm (~8 in.) and rotten logs have longer time-lags than 1,000 hours (Deeming and others 1977).

Table 2-2—Fuel moisture time lag, size class and description (Schroeder and Buck 1970). These size classes are commonly used in fire danger rating (Deeming and others 1978), fire behavior prediction (Rothermel 1972, Albini 1976, Andrews 2008), and fuel consumption calculations (Reinhardt and others 2005, Ottmar and others 2007).

Time lag	Size class, area/volume (range), cm (in)	Common surface m^{-1} (ft^{-1})	Fuel description
1 hour	<0.64 cm (<0.25 in)	630 to 10,800 m^{-1} (192 to 3300 ft^{-1})	lichens, mosses, weathered pine needles, loose leaf litter, grass straw
10 hour	0.64 - <2.54 cm (0.25 - <1.0 in)	157 to 629 m^{-1} (48 to 192 ft^{-1})	fresh pine needles, twigs
100 hour	2.54 - 7.62 cm (1.0 - <3.0 in)	52 to 156 m^{-1} (16 to 48 ft^{-1})	branch wood
1,000 hour	7.62 - 22.86 cm (3.0 - 9.0 in)	17 to 51 m^{-1} (5.3 to 16 ft^{-1})	sound logs

Finely divided (small) fuel particles have high SAVs, wet and dry quickly, and ignite and burn out quickly. The larger the SAV, the faster particles ignite and burn (table 2-2). Anderson (1969) determined that the duration of flaming was a function of particle diameter. Fuel pieces burn at an approximate rate of 3.15 minutes per centimeter of diameter (8 minutes per inch). Similarly, Harmathy (1972, 1976) found that the duration of smoldering was approximately as long as that of flaming. Thus the total duration of fuel burnout, flaming plus smoldering, is around 6.3 minutes per centimeter (15.75 minutes per inch) of fuel diameter consumed (Peterson and Ryan 1986). Thus, for example, if woody fuels up to 3 cm (1.2 in) in diameter were consumed on an area then a rough estimate of the duration of heating would be about 19 minutes. As available fuels in wildland fires burn at a relatively fixed rate, increasing the rate of spread also increases the depth of the flame zone in addition to increasing the length of the flames (fig. 2-2). This translates directly into higher fireline intensity, greater radiative heat flux, and an increased potential for damage to exposed cultural resources (sidebar 2-1).

Fuel particle characteristics vary continuously in space and time. In all but the most homogeneous of fuel-beds (e.g., productive grasslands), the mass and size distribution of fuels varies across an area with varying height as the physiognomy of the vegetation changes. Fuel particles change moisture content as a function of their size, relative humidity, and temperature (Sandberg and others 2001; Schroeder and Buck 1970; Van Wagtendonk 2006) (table 2-3) (fig. 2-4a). That variation is large relative to the spatial and temporal scales over which fires burn in natural communities. Thus, in practice, fuels are not described on the basis of individual fuel particle attributes, rather they are described in aggregate at the next higher scale as an agglomeration of several types of fuel (fig. 2-4b), referred to as a fuel complex or a fuel bed. In the Rothermel model and its variants (Andrews 2005; Deeming and others 1977; Finney 1998; Rothermel 1972; Scott 1998), fuel beds are described in the form of stylized fuel models (Albini 1976; Anderson 1982; Scott and Burgan 2005) that describe the mass per unit area, physical distribution (weighted particle size, fuel bed depth, bulk density), and chemistry (heat, moisture, and mineral content) of the surface fuels. Common U.S. terminology is the "Anderson-13" (Anderson 1982) and the "Scott and Burgan-40" (Scott and Burgan 2005). In contrast, the Canadian Forest Fire Behavior Prediction System (FBP) organizes fuel types into 16 discrete fuel types where the user selects the fuel type that best fits a particular situation. Fuel types in the FBP system are described qualitatively, rather than quantitatively (Forestry Canada 1992; Wotton and others 2009).

Fuel compactness refers to how tightly packed fuel particles are within the fuel bed. Compactness is described as a weight of fuel per unit volume of the fuel bed. It is estimated by measuring depth and loading of fuel by a standard methodology. The most commonly used technique in the United States is the planar intersect (Brown 1974; Brown and others 1982). Increasing density of fuels like grasses, woody debris, shrubs and forbs increases the amount of available fuels. Compactness influences drying rate and heat transfer during a fire. The more compact the fuels, the slower the drying rate. Maximum combustion occurs when particles are close enough together to effectively transmit heat by radiation and convection but far enough apart to not restrict oxygen flow to burning fuels.

It is important to understand that the emphasis for focusing on surface fuels is a reflection of the historic need to predict fire behavior for fire control purposes. Operational fire behavior prediction systems in the United States are based on the semi-empirical Rothermel (1972) mathematical model and in Canada on empirical field data (Stocks and others 1989; Hirsch 1996). These were developed to predict fire potential for strategic and tactical fire planning and management, not for predicting fire effects. One problem with using current fire behavior prediction systems in ecological studies is that they do not predict all of the combustion and, therefore, all of the energy released over the duration of the fire (c.f. Johnson and Miyanishi 2001; Ryan 2002). In particular they are insufficient for understanding below-ground effects. Thus, other fuel bed descriptors are common in the fire science and ecology literature (for example, see Barrows 1951; DeBano and others 1998; Ottmar and others 2007; Pyne and others 1996; Sandberg and others 2001, 2007). These fuel bed components are described on the basis of the physiognomic characteristics (tree, shrub, grass, forb, moss, etc.) (figs. 2-4a,b). Fuels are described typically on the basis of the stratum in which they occur (ground, surface, canopy) (table 2-3), how the type of fuel burns, (the dominant combustion characteristic such as smoldering vs. flaming), and potential duration of burnout during severe fire weather (Ottmar and others 2007; Sandberg and others 2001, 2002).

Conventional nomenclature defines fuels based on whether they are alive or dead, their availability for burning, their physical size, and chemical properties. Conceptually, total biomass is the sum of all plant material on the site and includes both above-ground and below-ground carbon. Historically, little organic mass within the mineral soil burns; therefore, the fire literature typically ignores the below-ground fraction. However, buried soil wood (e.g., rotten roots) may be of concern in some archaeological contexts (see chapter 7). Total aboveground biomass is the site's total dry mass of living and dead plant tissue found above

Table 2.3—Fuel bed strata and categories, and their physiognomic and gradient variables (from Ottmar and others 2007).

Fuelbed strata	Fuelbed categories	Physiognomic variables	Gradient variables
Canopy	Tree	Canopy structure Crown type	Canopy height Height to live crown Percentage cover
	Snag	Snag class	Diameter Height Snags per acre
	Ladder fuels	Vegetation type	Significance
Shrub	Shrub	Foliage type Growth habit Accelerant potential	Percentage cover Height Percentage live vegetation
	Needle drape		Significance
Low vegetation	Grass/sedge	Leaf blade thickness Growth habit	Percentage cover Height Percentage live vegetation
	Forb		Percentage cover Height
Woody fuel	Sound wood	Size class	Loading (tons/acre) Fuelbed depth
	Rotten wood	Size class	Loading (tons/acre)
	Stumps	Decay class	Stems/acre Diameter
	Woody accumulations	Piles, windrows or jackpots Clean or dirty	Height Width Length Number/acre
Moss/lichen/litter	Moss	Moss type	Percentage cover Depth
	Lichen		Percentage cover Depth
	Litter	Litter type Litter arrangement	Percentage cover Depth
Ground Fuel	Duff	Character	Depth Percentage rotten wood
	Basal accumulation	Accumulation type, e.g. litter, bark slough	Depth Trees per acre affected

the mineral soil. Above-ground biomass is further divided based on whether it is alive or dead. Live and dead fuel may be broken down into total and available fuel, as illustrated in the Venn diagram (fig. 2-5). Total fuel is the total amount of biomass capable of burning in a given area under a worst-case scenario. Available fuel is that biomass that actually burns in a specific fire. Total above ground biomass (≥ total fuel ≥ available fuel) is the total of all carbon stored on the site above the mineral soil including such things as living tree boles that are not consumed by surface or crown fires. In figure 2-5, the degree to which the Venn areas represented by the biomass classes are similar or different varies with the biome ranging from a tall grass prairie, where available fuel, total fuel, and above ground biomass are essentially equal under drought conditions, to a rain forest where an initial fire leaves substantial unburned biomass in the stems and canopy. The magnitude of these inequalities varies with the physiognomic structure of the biome and the prevailing moisture and wind at the time of the fire. Differences are small in grasslands and large in long undisturbed forests. The total amount of fuel available on a site depends on the stand structure and plant composition as well as the site's disturbance history (Graham and others 2004; Peterson and others 2005). "Structure" includes the quantity, distribution, and horizontal and vertical arrangement of live and dead trees, understory vegetation, woody debris, litter, and humus (Artsybashev 1983; Brown and Bevins 1986; Johnson 1992; Ryan 2002).

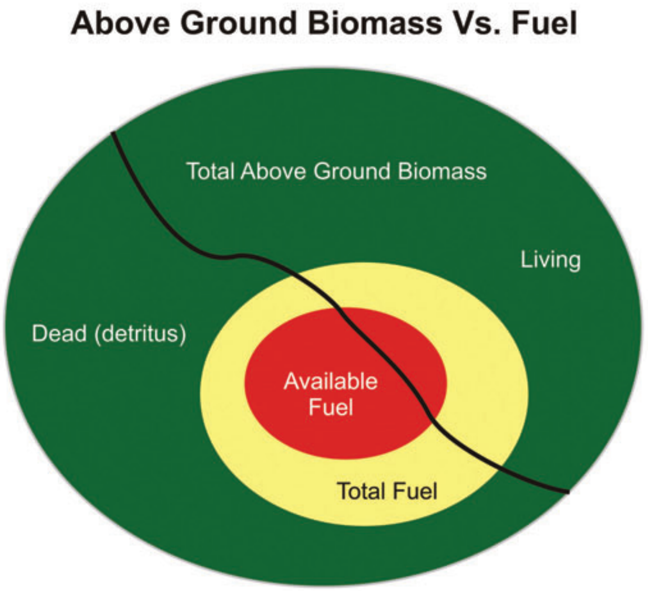

Figure 2-5—Venn diagram schematic representation of classes of biomass and their potential availability for combustion in a wildland fire. The degree to which live vs. dead fuel (black line) dominates a fuel complex varies by the biome, site disturbance history, seasonal phenology, and climatic cycles (e.g., drought vs. wet).

Fuel moisture is the single most important factor determining how much of the total fuel is available for combustion (Albini and others 1995; Nelson 2001). Moisture content is expressed as a percentage of water to the dry weight of fuel.

$$\{[(\text{wet} - \text{dry})/\ \text{dry}] \times 100\} = \text{mc}\% \qquad [1]$$

The moisture content of fine fuels is critical because they are the primary carriers of fire. Increasing moisture content reduces the likelihood that an ignition will lead to a propagating fire, and reduces the available fuel fraction. Within the range of moistures where fires can spread, increasing moisture content increases the duration of burning, and possibly leads to more emissive flames due to less efficient burning (Thomas 1970). Once conditions for fire spread are met, the moisture content of longer time-lag fuels becomes important to predicting below-ground fire effects. Wind increases the burning rate and decreases the duration of burnout (Cheney 1981; Miyanishi 2001).

The primary factor distinguishing living fuels versus dead fuels is their moisture content. Dead woody fuels (twigs, branches, logs) rarely exceed 30 to 35 percent moisture, the fiber saturation point on a dry mass basis, but may be as low as 2 or 3 percent during extended dry spells. In contrast, live fuels may have moisture contents approaching 300 percent early in the growing season, and rarely drop below 80 percent prior to senescence. In contrast to woody fuels, dead herbaceous fuels are typically less dense, have more pore space, and are thus capable of holding more free moisture at saturation. However, they are invariably much dryer than when they were alive. Fuels in an advanced state of decomposition, such as rotten logs and organic soil horizons, can hold much more moisture (up to 250 percent moisture content and occasionally higher). Rotten fuels can also ignite and burn at much higher moisture contents, approaching 200 percent under ideal burning conditions. The transition from solid fuel to rotten is a gradual process, often characterized by decay classes (Marcot and others 2004). Often, only a portion of the total above-ground biomass is capable of burning. In forests, for example, solid tree boles are too widely spaced to mutually reinforce each other's combustion. Even in the most destructive fires the trunks and most branches on standing live trees are not consumed. In contrast, in grasslands, virtually all of the above-ground biomass is available fuel under severe burning conditions.

The fire environment concept can be extended from its suppression-derived simplicity to a more ecological construct (fig. 2-6a). Fire behavior varies in time and space with changes in the terrain, weather, and vegetative structure and whether or not the area experiences a head fire, flank fire, or backing fire. As the fire behavior changes so do the effects (fig. 2-6b) (from Ryan 2002).The extension of the fire environment concept to ecological studies requires that fuels be considered in the broader context of the structure of biomass on the site. **Structure** defines the total amount of biomass that can be burned and, therefore, the total energy that can be released from all combustion phases in a fire. The size distribution of the structural components defines the rate at which energy will be released during favorable burning conditions. The rates at which fuels wet, dry (Nelson 2001), and burn (Anderson 1969) are functions of particle surface-area. These rates can be approximated from diameter for most dead fuels above the ground fuel stratum (i.e., above the duff layer) (table 2-2).

Given that the various components of a fuel bed have rather unique burning characteristics, fires burn throughout a continuum of energy release rates and durations depending on the complexity of fuel elements present (appendix) (Artsybashev 1983; Rothermel 1991; Rowe 1983; Van Wagner 1983).

Ground fuel includes organic matter below the loose surface litter including deep duff (fermentation and humus soil horizons), tree roots, decomposing buried logs, duff mounds around tree bases, and rodent middins (fig. 2-4). Peat and organic muck soils are also ground fuels. Because of the lack of aeration, ground

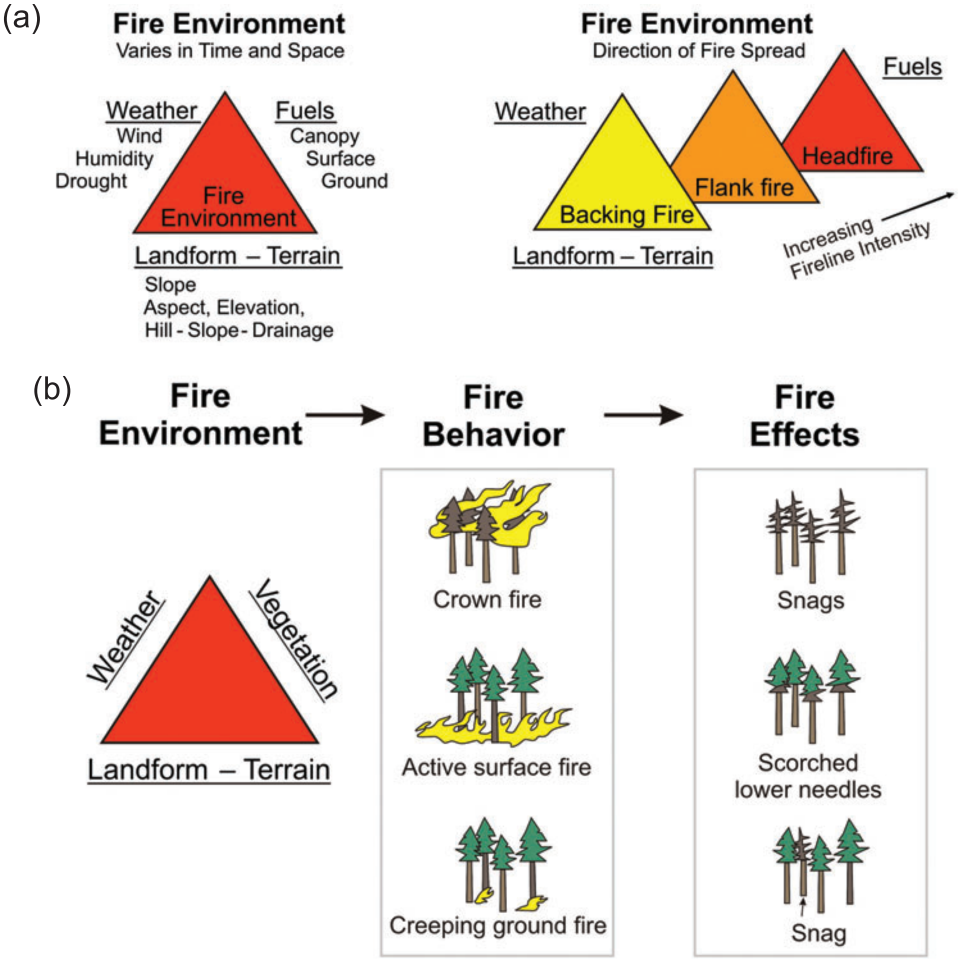

Figure 2-6—Fire environment, behavior, and effects (from Ryan 2002).

fires burn these densely compacted organic soil horizons primarily by smoldering combustion (fig. 2-7). Such fires typically burn for hours to weeks, exhibit forward rates of spread in the range of a few decimeters to a few meters (feet to yards) per day, and exhibit temperatures at a point in excess of 300 °C (572 °F) for several hours (Agee 1993; Frandsen and Ryan 1986; Grishin and others 2009; Hartford and Frandsen 1992; Ryan and Frandsen 1991) (e.g., fig. 2-8). Burning rates and intensities of organic soils vary somewhat with moisture content and availability of air. Frandsen (1991a) found the rate of spread in laboratory analysis of duff fuels to be on the order of 3 cm (1.2 in) per hour. The conditions necessary for ground fires are organic soil depth greater than about 4 to 6 centimeters (1.6 to 2.4 in.) and extended drying (Hawkes 1993; Miyanishi 2001; Miyanishi and Johnson 2002; Palmer 1957; Reinhardt and others 1997). Duff thinner than this can actually buffer mineral soil (Bradstock and Auld 1995; Valette and others 1994) and artifacts from significant heating associated with the passage of the flaming front. This is because the energy lost from the duff surface exceeds that produced by burning duff and the fire self extinguishes after the passage of the flaming front.

The occurrence of ground fires is strongly dependent on the moisture content of the organic horizon (Brown and others 1985; Frandsen 1987, 1997; Grishin and others 2009; Hawkes 1993; Hungerford and others 1995; Lawson and others 1997a,b; Miyanishi 2001; Miyanishi and Johnson 2002; Reardon and others 2007, 2009; Rein 2009; Reinhardt and others 1991; Sandberg 1980; Van Wagner 1972). In particular, peat and organic muck soils fuels, which require extended drought or disruption of ground water flow, reach moisture contents low enough to burn (Grishin and others 2009; Hungerford and others 1995; Reardon and others

Figure 2-7—Smoldering combustion in ground fuels (a) creeping surface fire igniting duff mound beneath old growth western larch, *Larix occidentalis* in the 2005 Girard Grove prescribed burn, Seely Lake Ranger District, Lolo National Forest, Montana; (b) burnout of smoldering duff mound in (a); (c) burnout of organic muck soil on the 1994 Fish Day wildfire, Croatan National Forest, North Carolina; and (d) smoldering duff from squirrel midden in jack pine forest, Northwest Territories, Canada. ,

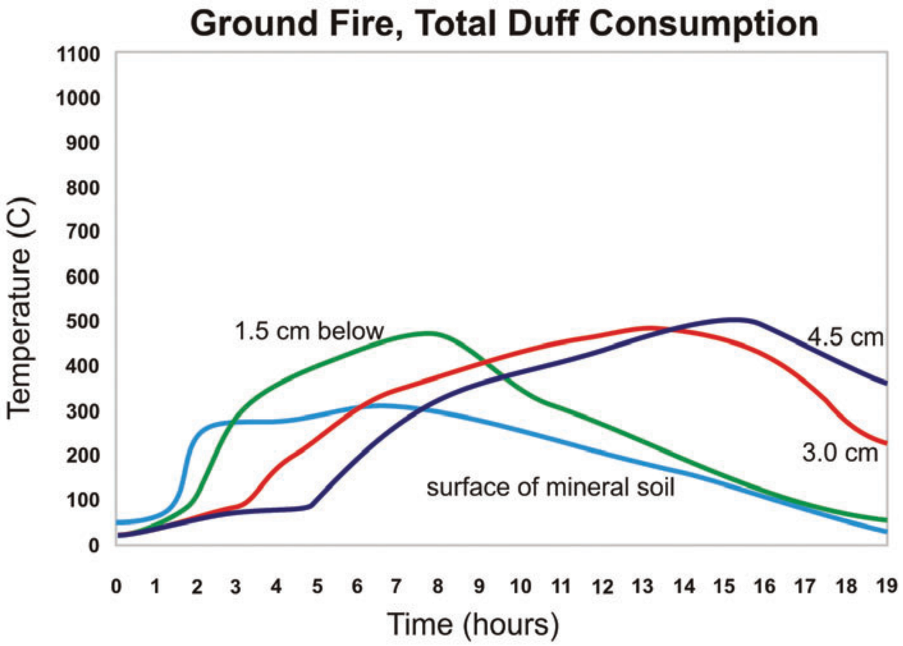

Figure 2-8—Example of temperatures associated with smoldering ground fire in western larch *Larix occidentalis* duff, Lolo National Forest, Montana. Duff depth = 6.5 cm (2.6 in.), moisture content = 18.3% (from Hartford and Frandsen 1992).

2007, 2009; Rein 2009; Rein and others 2008). Ground fuels are good insulators and protect deeper organic strata and the mineral soil from heating during the passage of surface and crown fires (fig. 2-9). However, when ground fuels are dry enough to burn, they are ignited by the passage of the flaming front. Surface fire penetrates the litter and fermentation layer where pine cones, branches, or rotten wood create a localized hot spot. Once ignition is established in the humus or peat soil, the fire propagates laterally evaporating moisture and raising dry organic soil up to combustion temperatures (endothermic phase) where smoldering combustion occurs (exothermic phase.) (Grishin and others 2009; Hungerford and others 1991, 1995; Rein 2009; Rein and others 2008). Ground fuels have a slow burning rate and burn independently from surface and crown fires, so most ground fuels are consumed after the flaming front has passed, often some hours after passage of the flaming front (Artsybashev 1983; Hungerford and others 1995; Rowe 1983; Van Wagner 1983). An exception occurs when surface fires are burning in heavy loadings of coarse woody debris (CWD), which is a legacy from previous disturbances (e.g., logging slash, insect and disease epidemics, or storm damage). Even in such situations, CWD rarely covers more than 10 percent of the surface area of the forest floor, which is small in comparison to that covered by organic soil horizons such as duff (Albini 1976; Albini and Reinhardt 1995, 1997; Peterson and Ryan 1986). Thus burnout of ground fuels is the primary source of deep heating in mineral soils. When duff is too wet to burn, heating from above is negligible except under heavy concentrations of burning CWD.

Surface fuels are those fuels that support surface flaming: recently fallen, partially decomposed loose litter (dead leaves and conifer needles), mosses, lichens, grasses, forbs, low shrubs, arboreal regeneration, fine woody debris (FWD), CWD, and stumps. The surface fuel stratum is defined as those being above the ground fuels (i.e., organic soil horizons) and below the canopy stratum, and is normally <2.0 m, (~6 ft)) (fig. 2-4b). The intensity of a surface fire depends on the mass and type of total fuel and prevailing moisture, wind, and slope conditions on the site (i.e., the fire environment).

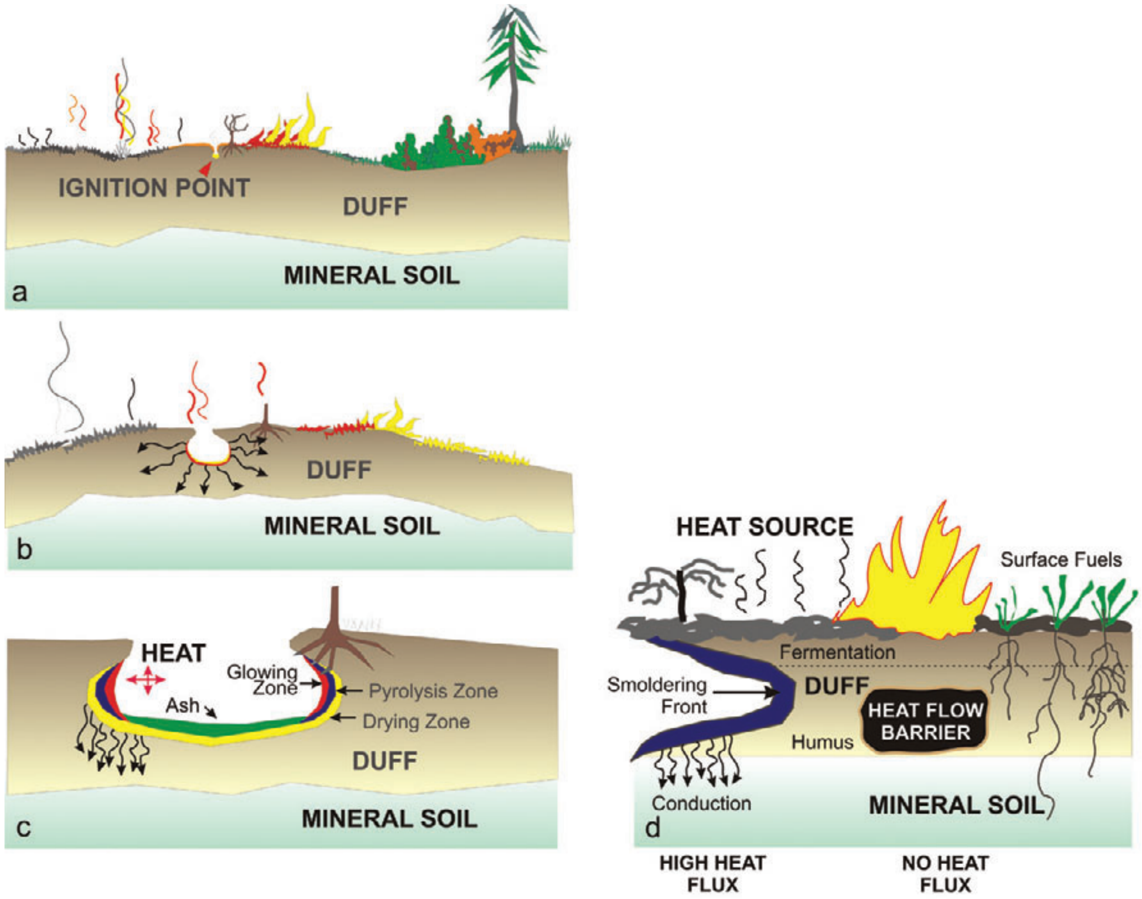

Figure 2-9—Schematic of duff burnout (adapted from Hungerford and others 1991, 1995).

As the vegetative physiognomy of forests, woodlands, shrublands, grasslands, and wetlands vary across the landscape surface, fires are likewise highly variable. Surface fires in light flashy fuels, such as grasslands, have a broad range of intensities often producing surface temperatures in excess of 300 °C (572 °F), but because of the high surface-area-to-volume ratio of grass fuels and the relatively low fuel bed compactness burn durations last only for 1 to 2 minutes (fig. 2-10). Under marginal burning conditions, surface fires creep along the ground at rates of decimeters (~1/3 foot) per hour with flames less than 5 decimeters (<2 feet) (appendix). As fuel, weather, and terrain conditions become more favorable for burning, surface fires become progressively more active with spread rates ranging from tens of meters to kilometers (yards to miles) per day. The duration of forest surface fires is on the order of 1 to a few minutes (Butler and others 2004; Cruz and others 2006a,b; Despain and others 1996; Frandsen and Ryan 1986; Hartford and Frandsen 1992; Vasander and Lindholm 1985) except where extended residual secondary flaming (fig. 2-2a) occurs beneath logs or in concentrations of CWD where flaming combustion may last a few hours resulting in substantial soil heating

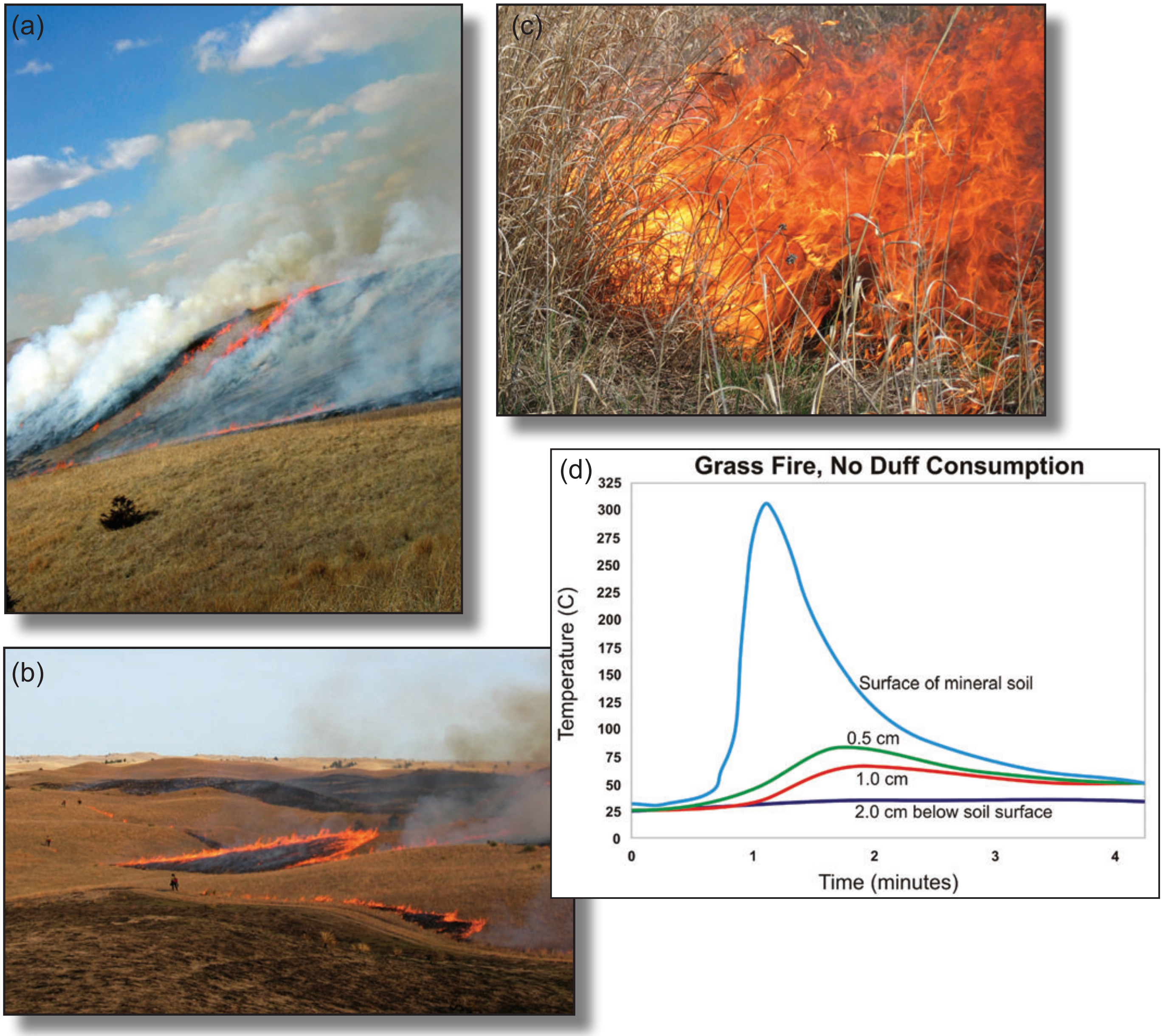

Figure 2-10—Surface fire in grasslands (a) backing fire in short-grass prairie (photo M. Lata); (b) strip head fires in short-grass prairie (note range of flame lengths, fire intensities from the back, flank, and head of the fires) (photo M. Lata); (c) intense head-fire in heavy grass fuels; and (d) temperatures associated with surface fire a in grass fuel bed (from Ryan 2002).

(Hartford and Frandsen 1992; Monsanto and Agee 2008; Odion and Davis 2000; Werts and Jahren 2007). If canopy fuels are plentiful and sufficiently dry, surface fires begin to transition into crown fires (Scott and Reinhardt 2001; Van Wagner 1977). Given that fine surface fuels burnout quickly by flaming combustion, it follows from the fireline intensity equation (eqn. 2, discussed in the Fire Intensity section), that increasing the available fuel loading (mass per unit area) will increase the intensity of the fire as reflected both in the size of the flames and the temperatures experienced at the soil surface (Stinson and Wright 1969; Wright and others 1976) (fig. 2-11). The considerable variation in surface temperatures reported from burning fine surface fuels (see Wright and Bailey 1982, ch. 2 for review) reflects the complexity of free-burning fires where local variations in fuel load and wind result in flames of varying emissivity and, therefore, potential damage to cultural resources.

Aerial or **crown** fuels include live and dead burnable biomass in the forest and woodland canopy stratum above the surface fuels (>2 m, ~ 6 ft.) (fig. 2-4b): branches and foliage of trees and tall shrubs, snags, epiphytes, hanging mosses and lichens (figs. 2-12a,b), (table 2-2). While surface fires are the dominant type of wildland fire, ground and crown fires commonly occur. The prediction of crown fires is an active area of fire research (see Cruz and Alexander, 2010, for recent review). Critical gaps in our understanding include (1) how moisture content affects the fraction of the crown biomass burned during a crown fire, (2) how to define crown volume, (3) how to define the distribution of biomass within that volume, and (4) how to define the continuity between surface fuels and canopy fuels. The height, shape, and density of crowns vary from tree to tree; trees are not uniformly distributed in natural stands. Surface fuels are of an irregular height; likewise the base of the crown (i.e., height of lower branches) varies from tree to tree, thus, the gap between surface and canopy fuels is often difficult to define. The following paragraphs are intended to inform cultural resource specialists about these important concepts.

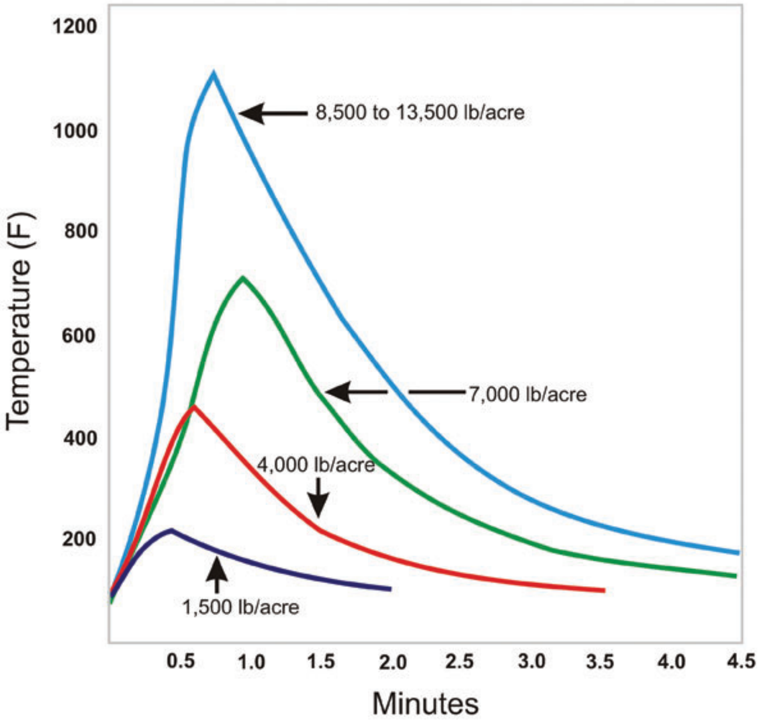

Figure 2-11—Variation in temperature history (maximum temperatures and durations) associated with increasing amounts of available fuel in a Texas grassland. Environmental conditions during the experimental burns were air temperatures, which varied from 21 °C to 27 °C (70 °F to 80 °F); relative humidity, which ranged from 20 to 40 percent; and wind speed, which varied from 13 to 24 km/hr (8 to 15 mph) (From Wright and others 1976).

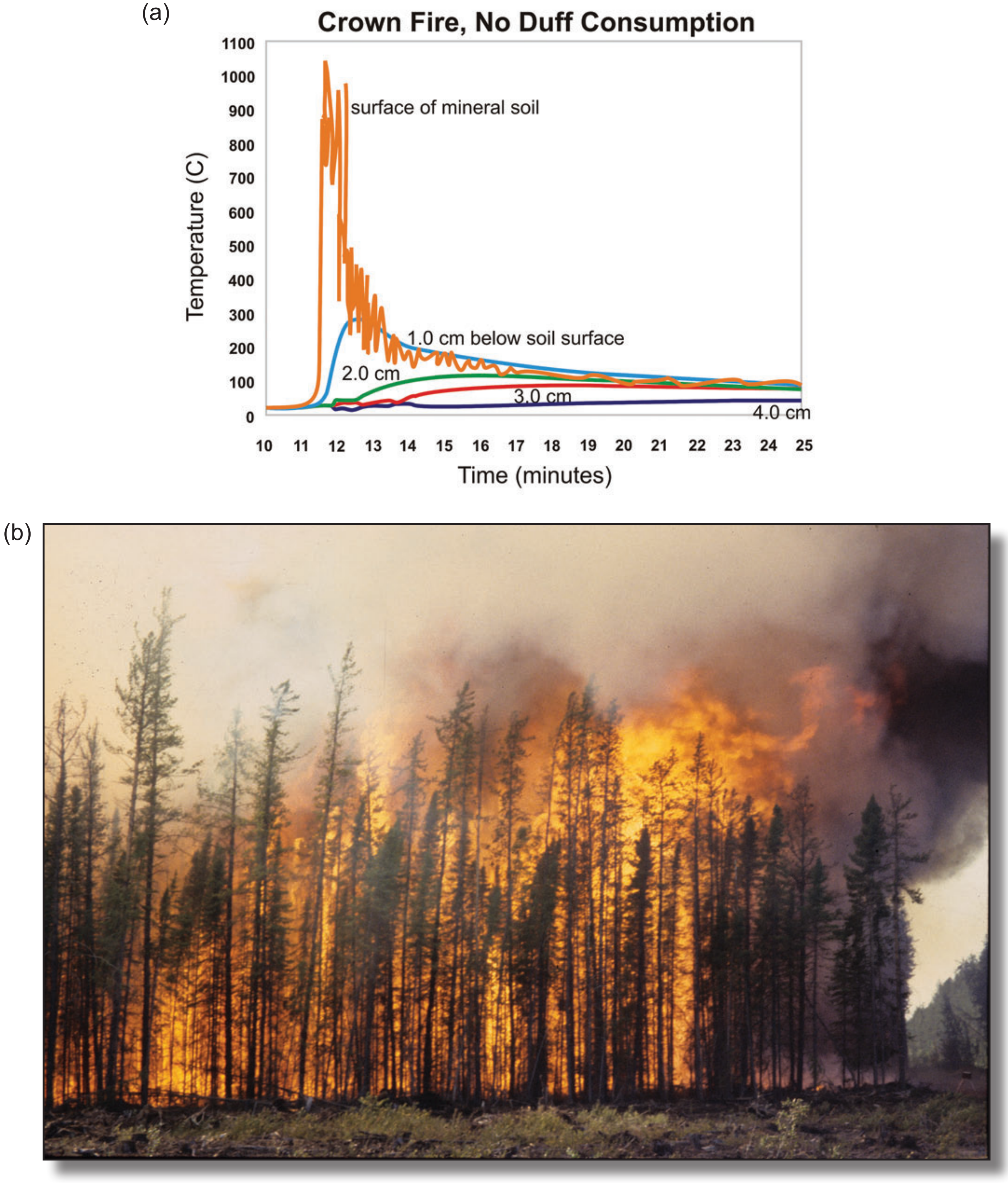

Figure 2-12—Crown fire in coniferous forest (a) example of temperatures associated with a crown fire in jack pine (*Pinus banksiana*) in the Northwest Territories, Canada. Such fires typically produce temperatures in excess of 1000 °C (1832 °F) for about 1 minute (from Ryan 2002); (b) photograph of crown fire associated with (a).

Canopy fuels are predominantly fine fuels and are quickly consumed. Thus crown fires exhibit the maximum energy release rate but are typically of short duration, 30 to 80 seconds (fig. 2-12b). On rare occasions, under specialized conditions, crown fires can occur without the support of a surface fire. Such fires are referred to as **independent crown fires** (Van Wagner 1977). More commonly, crown fires are tightly coupled with the surface fire in a continuous three-dimensional involvement of surface and crown fuels advancing as a unified flaming front referred to as an **active crown fire**. Commonly, individual trees and clumps of trees experience torching in association with the passing of a surface fire. This is referred to as a **passive crown fire** (Van Wagner 1977).

As a fire burns across the landscape, it encounters different communities with varying site productivity and differing disturbance histories that result in varying stand structures and flammability (Graham and others 2004; Peterson and others 2005) (fig. 2-13). For example, stands with a high open crown (canopy) and short understory fuels have poor vertical fuel continuity. Such stands will frequently carry a surface fire due to increased sunlight and wind at the surface (Albini 1976; Kunkel 2001; Stocks and others 1989; Wotton and others 2009) but have a low crown fire potential because of the large gap between surface aerial fuels (Artsybashev 1983; Grishin 1997; Scott 1998; Scott and Reinhardt 2001; Van Wagner 1977, 1993). In contrast, forest stands with a dense understory of shrubs or immature trees have relatively high vertical fuel continuity. Such stands can support intense surface fires leading to crowning and torching of the tree canopy stratum. If the canopy stratum is a patchy over-story, then the stand has poor horizontal fuel continuity in the canopy layer. Such stands readily support passive crowning (torching) and spotting under low relative humidity, especially when surface fuels are in an

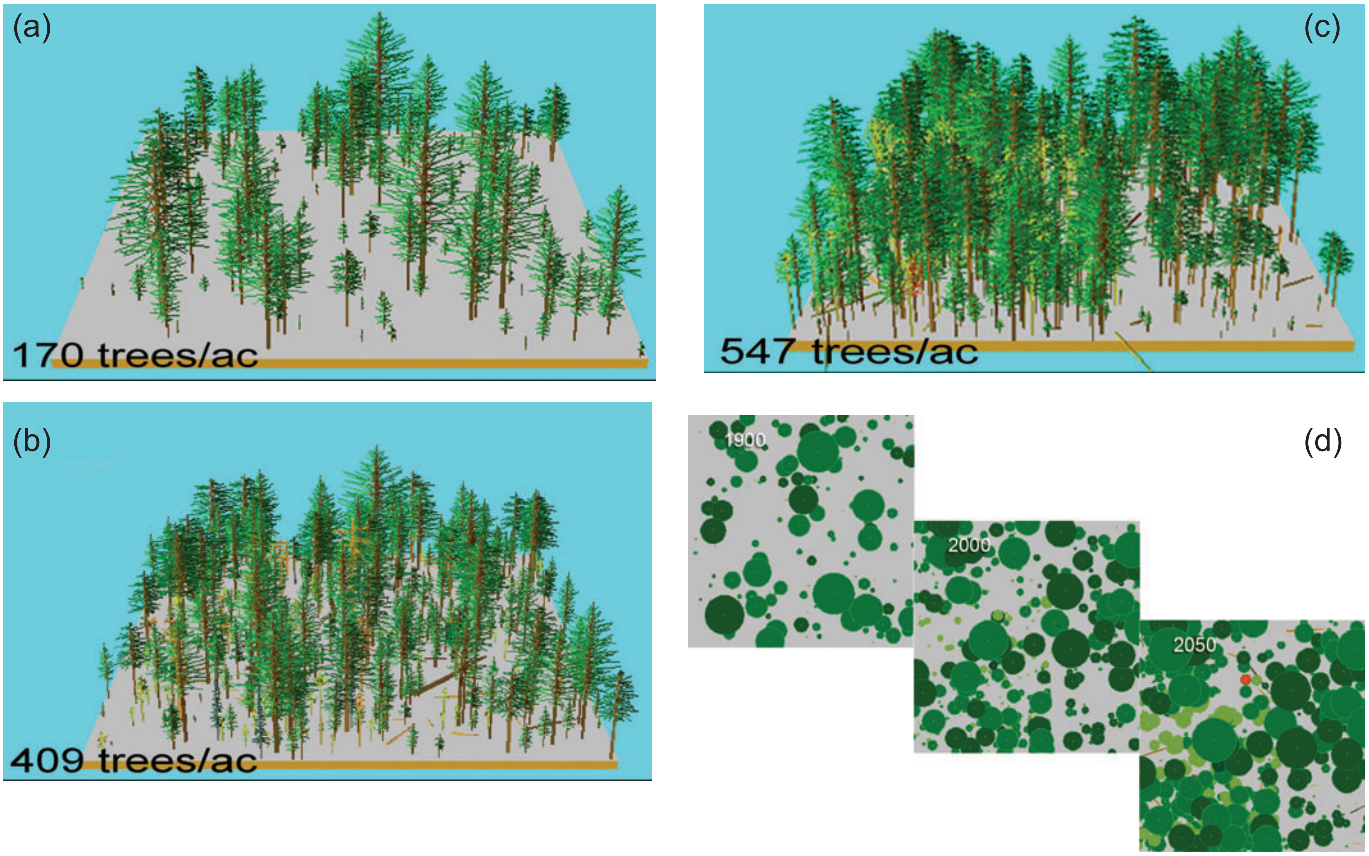

Figure 2-13—Fuel continuity. Increasing stand density on a site as a function of natural succession leading to an increase in horizontal and vertical fuel continuity. Illustrated are 170 trees per acre (420 trees per hectare) in 1900 (a), 409 trees per acre (1010 trees per hectare) in 2000 (b), 547 trees per acre (1351 trees per hectare) in 2050 (c), and horizontal fuel continuity from an overhead view of frames a-c (d). Crown cover is expected to increases to 80 percent by 2050 leading to a significant increase in crown fire potential (from Smith and others 2000). Simulations were done using FFE-FVS (Crookston and others 2000, i.e., prior to the 2002 Hayman Fire) with data from Cheesman Reservoir, Pike National Forest, Colorado.

advanced state of curing. Stands with high vertical and horizontal fuel continuity are less likely to burn because of the typically moister microenvironment, but such stands have the highest crown fire potential when fires burn under drought, low relative humidity, or high wind conditions (Alexander 1998; Cruz and Alexander 2010; Finney 1998, 1999; Scott 1998; Scott and Reinhardt 2001; Van Wagner 1977, 1993). The availability of fuels varies not only in space, but also in time with changes in weather (principally relative humidity, temperature, and drought) (Bessie and Johnson 1995; Flannigan and Wotton 2001; Johnson 1992; Schroeder and Buck 1970). Spatial variation in the fire environment leads to varying fire severities and burn mosaics as fire spreads across the landscape.

Ignition: How Fuel is Ignited Affects Fire Behavior and Effects—Taken collectively, the vegetation structure, weather, and terrain constitute the biophysical fire environment (DeBano and others 1998; Pyne and others 1996) (fig. 2-6a), which describes the potential fire behavior and effects. Actual fire behavior varies with how the specific area is burned. Independent of the biophysical environment in which the fire is burning, major differences in fire behavior are associated with the location on the fire's perimeter, that is, whether an area is burned by a heading, flanking, or backing fire (Catchpole and others 1982, 1992; Cheney and Sullivan 2008; Ryan 2002) (figs. 2-3, 2-6b). The heading portion of the fire burns with the wind or upslope. The backing fire burns into the wind or down slope. The flanking fire burns perpendicular to the wind's or slope's axis. The direction of fire spread is a function of the slope and wind vectors, with the latter dominating except at low wind speeds (Albini 1976; Finney 1998; Rothermel 1972). The intensity of both heading and backing fires are dependent on the strength of the wind and steepness of a slope. Commonly, fireline intensity in a backing fire is on the order of 0.1 to 0.2 times that of a heading fire in a given biophysical environment, while flanking fires are about 0.4 to 0.6 times the head-fire intensity (Catchpole and others 1992). Variations in the fire environment and location on the fire perimeter lead to significant variations in the fire behavior and effects (fig. 2-6b). For example, it is common to see fires spread across a slope running with the wind when the vegetation structure is not sufficient and continuous enough for the fire to carry up the slope. Thus the ignition pattern that is used in a restoration burn can also be expected to affect the pattern of fire behavior and the resulting effects.

In summary, fires burn in varying combinations of ground, surface, and crown depending on the local conditions at the specific time a fire passes a point. Changes in surface and ground fire behavior occur in response to subtle changes in the microenvironment, stand structure, and weather leading to a mosaic of fire treatments at multiple scales in the ground, surface and, canopy strata. Crown fires are of high intensity (energy release rate) and of short duration. Ground fires are of low intensity and long duration. Surface fires are intermediate to crown and ground fires and cover a wide range of intensities and duration depending on the amount of available fuel loading and its particle size distribution. Heavy concentrations of coarse woody debris can result in long duration high intensity heating of the soil. However, such concentrations typically cover only a small proportion of the surface of the ground (Albini 1976; Brown and others 2003; Peterson and Ryan 1986). In most forests, either duff or peat covers a much greater proportion of the surface than FWD and CWD combined. The burnout of these organic soil horizons by smoldering combustion is the primary source of mineral soil heating. During crown and surface fires the majority of heat released by combustion is transferred to the atmosphere and surrounding exposed surfaces by radiation and convection. During ground fires, much of the heat that is released is transferred into the soil by conduction. When crown fires or intense surface fires occur over dry organic soil horizons these layers can continue to burn for several hours after the passage of the flaming front leading to high heat release both above and below ground (fig. 2-14). The practical significance of ground, surface, and canopy fires to cultural resource management will be discussed in subsequent sections.

Fire Intensity, Depth of Burn, and Fire Severity

Fire intensity and fire severity are terms that are often used in fire literature; however, there is considerable confusion about their use (see Keeley 2009 for discussion). Part of the confusion in their use stems from the fact that the terms may be used both informally, as a normal matter of discourse, or they may be used formally as terms defined by the user. Definitions vary somewhat depending on the scale of the fire being investigated.

Fire Intensity

Fire intensity is used by researchers in the United States and Canada to describe the amount of energy released in a given area during the passage of a fire front (Alexander 1982; DeBano and others 1998; Kaufmann and others 2007; Pyne and others 1996; Rothermel and Deeming 1980; Van Wagtendonk 2006; Wotton and others 2009). This measurement relates the length and depth of a fire front to the amount of heat energy being released (Byram 1959) (Equation 2, and fig. 2-6). In turn, these values are used to understand

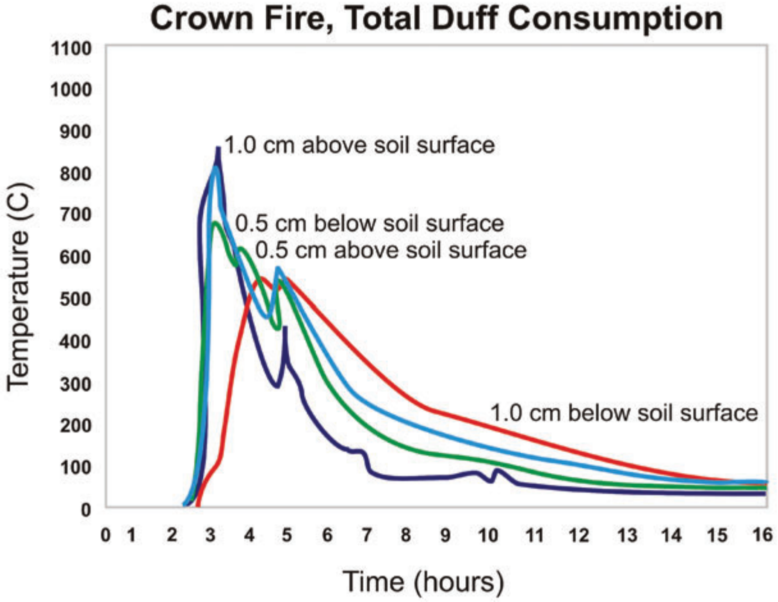

Figure 2-14—Temperatures associated with a high intensity, long duration fire in a whitebark pine (*Pinus albicaulis*) stand, Clearwater National Forest, Idaho. Passive crowning (torching) was followed by sustained flaming in a cluster of logs.

fire potential and level of fire suppression difficulty (Alexander and Lanoville 1989; Andrews and others 2011). Byram's (1959) definition of fireline intensity has become a standard quantifiable measure of intensity (Agee 1993; Alexander 1982; DeBano and others 1998; Johnson 1992; Rothermel and Deeming 1980; Van Wagner 1983; Van Wagtendonk 2006). Fireline intensity is the product of the fuel value (i.e., the fuel's heat content, the mass of fuel consumed, and the rate of spread (m/s)) (Byram 1959). It is a measure of the rate of energy release per unit width of the flaming front of the spreading fire. It does not address the residual secondary flaming behind the front nor subsequent smoldering combustion (fig. 2-2a) (Alexander 1982; Albini and Reinhardt 1995, 1997; Johnson and Miyanishi 2001; Rothermel and Deeming 1980). Fireline intensity can be written as a simple equation:

$$I = HWR \qquad [2]$$

where

I is Byram's (1959) fireline intensity (kW/m/sec or BTU/ft/sec),

H is the heat content of the fuel (kW/kg or BTU/lb or of fuel),

W is the weight of available fuel burned in the active flaming (spreading) fire front (kW/kg of fuel or BTU/lb), and

R is the forward rate of spread (m/sec or ft/sec).

Byram's fireline intensity is usually calculated from empirical observations of the rate of spread (R), weight of fuel consumed (W) and the heat content (H), which is normally taken from typical published approximate values, or it is predicted by fire behavior models (Albini 1976; Alexander 1982; Rothermel 1972; Rothermel and Deeming 1980). The challenge in managing fire is to determine how much, and what type of fuel will burn, and by what type of combustion. In Byram's (1959) equation (eqn. 2), the value of W is the weight of fuel consumed in the active flaming phase of the fire. W approaches the value for available fuel in fires where only fine dead fuels are consumed (such as the grass fire mentioned above) (fig. 2-11), or when coarser fuels are too sparse or wet to be ignited by the passing flame front. When these conditions are not satisfied, a portion of the available fuel is consumed in the secondary flaming and smoldering combustion phase. The burnout of these residual fuels does not contribute to the forward propagation of the fire (R in equation 2), but is often important for predicting fire effects related to soil heating (Busse and others 2005; Hartford and Frandsen 1992; Hungerford and others 1991; Monsanto and Agee 2008; Odion and Davis 2000). Figure 2-15 illustrates the total consumption of 1-, 10-, and 100-hour time-lag fuels as a function of fuel moisture content. In practice, because all combustion phases occur simultaneously (Urbanski and others 2009), it can be difficult to clearly identify which portion of the available fuel is burned in the

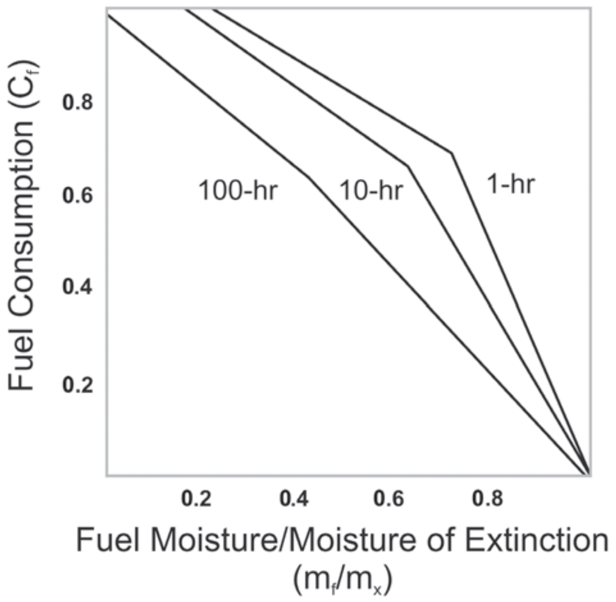

Figure 2-15—Fuel consumption and a function of the fuel's fractional fuel moisture content (M_f) and the fractional moisture content beyond which fuels typically no longer sustain combustion (M_x) except at very high packing ratios. The ratio m_f/m_x for 1-, 10-, and 100-hour fuels is 0.73, 0.51, and 0.38, respectively (from Peterson and Ryan 1985).

active flaming vs. residual secondary flaming and smoldering, but fuel consumption (Albini and Reinhardt 1995, 1997; Albini and others 1995) and smoke production (Bytnerowicz and others 2008; Sandberg and others 2002; Urbanski and others 2009) programs can be used as a guide. Alternatively some field studies measure flame length (Finney and Martin 1992; Deeming 1980; Rothermel and Deeming 1980; Ryan 1981; Simard and others 1989) to estimate fireline intensity (Albini 1981a; Byram 1959; Fernandes and others 2009; Nelson 1980). Flame length (fig. 2-2) is proportional to fireline intensity in a spreading fire and is a useful measure of the potential to cause damage to aboveground structures (Alexander 1982; Ryan and Noste 1985; Van Wagner 1973). Actual field measurement of fireline intensity requires sophisticated instrumentation (Butler and Dickinson 2010; Butler and others 2004; Kremens and others 2010). Thus field observers often calculate fireline intensity from ocular estimates of flame length, simple flame height sensors (Finney and Martin 1992; Ryan 1981; Simard and others 1989), or vegetation damage indicators (Norum 1977; Ryan and Noste 1985) and use known relationships between fireline intensity and flame length (Albini 1981a; Byram 1959; Fernandes and others 2009; Nelson 1980). The appendix contains photographic examples of a range of flame lengths associated with fire intensity classes (table A-1, fig. A-1.1 to A-1.5, appendix) (Ryan 2002).

Rothermel (1972) defined a somewhat different measure of fire intensity, the Reaction Intensity, which is the heat per unit area. This is commonly used in fire danger rating (Deeming and others 1977) and fire behavior prediction (Albini 1976; Andrews 1986; Scott 1998; Scott and Reinhardt 2001) in the United States. In contrast, the Canadian forest fire danger rating system (Stocks and others 1989) and the Canadian Forest Fire Behavior Prediction (FBP) System (Hirsch 1996; Taylor and others 1996; Wotton and others 2009) calculate the intensity of surface fires using Byram's (1959) equation.

Depth of Burn

Although infrequent, fire is capable of burning independent of surface fuels. When it moves through the crown alone (independent crown fire), there is often little surface and subsurface effect because of the short burning duration of canopy fuels. More commonly, crown fires and torching are associated with active or running surface fires (appendix table A-1). If the duff is dry, it is ignited by the passage of a surface fire. Then, duff greater than about 4 cm deep (1.6 in) can burn independently without continued flaming in surface fuels (Frandsen 1997; Lawson and others 1997a; Urbanski and others 2009) (fig. 2-16). During

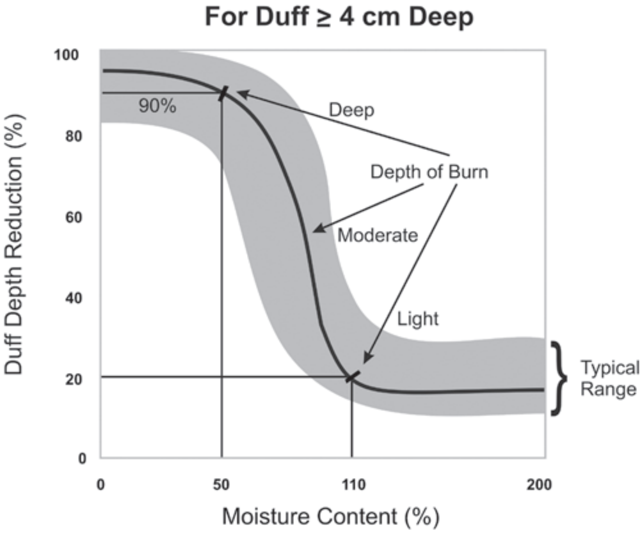

Figure 2-16—Illustration of duff consumption, percent of total duff available (%), as a function of lower duff (humus) moisture content for common forest conditions where duff is greater than 4 centimeters deep and able to burn independent of a surface fire if dry enough to burn. Shaded area represents the range of consumptions found in the literature. Deeper layers and those with less mineral content tend toward greater consumption for given moisture content.

glowing and smoldering combustion of surface and ground fuels, residence time is prolonged. The duration of smoldering can range from as little as 2 hours to more than 30 hours in deep organic soil horizons (Grishin and others 2009; Hungerford and others 1995; Reardon and others 2007, 2009; Rein and others 2008) (fig. 2-8). Given longer durations, heat may penetrate deeply into the soil profile. The term commonly used to describe the degree to which surface and ground fuels are consumed is "depth of burn."

Ryan and Noste (1985) summarized literature on depth of burn and charring of plant materials and developed descriptive characteristics. Their original descriptions were revised to reflect subsequent work (DeBano and others 1998; Feller 1998; Moreno and Oechel 1989; Pérez and Moreno 1998; Ryan 2002) and were published in the Rainbow volume on the *Effects of Fire on Soil and Water* (Neary and others 2005). A description of the characteristics that they developed is provided for clarification of subsequent discussion of fire effects. The appendix includes several examples of depth of burn classes.

Unburned: Plant parts are green and unaltered; there is no direct effect from heat.

Scorched: Fire did not burn the area but radiated or convected heat caused visible damage. Mosses and leaves are brown or yellow but species characteristics are still identifiable. Soil heating is negligible.

Light: In forests, the surface litter, mosses, and herbaceous plants are charred to consumed but the underlying forest duff or organic soil is unaltered. Fine dead twigs are charred or consumed but larger branches remain. Logs may be blackened but are not deeply charred except where two logs cross. Leaves of understory shrubs and trees are charred or consumed but fine twigs and branches remain. In non-forest vegetation, plants are similarly charred or consumed; herbaceous plant bases are not deeply burned and are still identifiable, and charring of the mineral soil is limited to a few millimeters (fractions of an inch).

Moderate: In forests, the surface litter, mosses, and herbaceous plants are consumed. Shallow duff layers are completely consumed and charring occurs in the top centimeter (0.4 in.) of the mineral soil. Deep duff layers or organic soils are deeply burned to completely consumed, resulting in deep charcoal and ash deposits but the texture and structure of the underlying mineral soil are not visibly altered. Deep ash deposits are sometimes confused with oxidized mineral soil. Ash is fine and powdery when dry, slick and greasy when wet, whereas oxidized soil retains pebbles and granularity and feels gritty. Trees of later successional, shallow-rooted species often topple or are left on root pedestals. Fine dead twigs are completely consumed, larger branches and rotten logs are mostly consumed, and logs are deeply charred. Burned-out stump holes and rodent middens are common. Leaves of understory shrubs and trees are completely consumed. Fine twigs and branches of shrubs are mostly consumed (this effect decreases with height above the ground), and only the larger stems remain. Stems of these plants frequently burn off at the base during the ground fire phase, leaving residual aerial stems that were not consumed in the flaming phase lying on the ground. In non-forest vegetation, plants are similarly consumed; herbaceous plant bases are deeply burned and unidentifiable. In shrublands, charring of the mineral soil is on the order of 1.0 centimeter (0.4 in.) but soil texture and structure are not clearly altered.

Deep: In forests growing on mineral soil, the surface litter, mosses, herbaceous plants, shrubs, and woody branches are completely consumed. Sound logs are consumed or deeply charred. Rotten logs and stumps are consumed. The top layer of the mineral soil is visibly oxidized, reddish to yellow. Surface soil texture is altered and, in extreme cases, fusion of particles occurs. A black band of charred organic matter 1 to 2 centimeters (0.4 to 0.8 inches) thick occurs at variable depths below the surface. The depth of this band is an indication of the duration of extreme heating. The temperatures associated with oxidized mineral soil are associated with flaming rather than smoldering. Thus, deep depth of burn typically only occurs where woody fuels burn for extended duration, such as beneath individual logs or in concentrations of woody debris. In areas with deep organic soils, deep depth-of-burn occurs when ground fires consume the root-mat or burn beneath the root-mat. Trees often topple in the direction from which the smoldering fire front approached.

Fire Severity

Fire behavior refers to the manner in which a specific fire burns the fuel bed (fuel complex) in a given terrain with the prevailing weather conditions at the time. Fire behavior prediction is concerned primarily with the characteristics contributing to the advance of a free-burning fire. This issue is more directly related to fireline intensity (Alexander 1982; Byram 1959; Ryan and Noste 1985). One problem with applying fireline intensity in ecological studies is that it does not predict all of the combustion or quantify all of the energy released during a fire (Johnson and Miyanishi 2001; Ryan 2002; Keeley 2009). In contrast, **fire**

severity is concerned with both the characteristics of the free burning fire as it spreads across an area and the characteristics of the stationary fire as it resides at a site (i.e., duration of burning), because it is the latter's characteristics that primarily determine how deep into the soil profile fire and heat can penetrate (Frandsen and Ryan 1986; Hartford and Frandsen 1992; Ryan 2002). Fire severity is a construct that describes the change in site properties/conditions due to fire. Fire severity describes the outcome rather than the process and is thus useful for understanding the ecological effects of fire on an ecosystem: the amount of organic matter lost from a location, vegetation mortality, and soil transformations (Feller 1998; Jain and others 2008; Kaufmann and others 2007; Keeley 2002; Ryan 2002). The same principles apply when considering the impacts of fire on cultural resources found within the soil profile.

Following a fire, researchers are able to better understand fire dynamics by quantifying fire intensity and duration (Neary and others 2005; Ryan 2002; Ryan and Noste 1985). Several authors have quantified the depth of burning into the ground (DeBano and others 1998; Feller 1998; Jain and Graham 2007; Jain and others 2008; Morgan and Neuenschwander 1988; Ryan and Noste 1985), and consumption (fig. 2-15) and depth of char in FWD and CWD (Albini and Reinhardt 1995, 1997; Costa and Sandberg 2004). When depth of burn/char measurements are coupled with estimates of flame length and fire spread direction, it is possible to recreate a fire's movement through a stand. By combining flame length and depth of burn/char measurements, researchers are able to create a two-dimensional matrix of fire severity, which may be a useful classification of the level of fire treatment for comparative analysis of fire effects within and between fires. For example, Ryan and Noste (1985) (appendix table A-3) assessed the effects of fire on tree crowns and ground fuels by visiting burned sites and measuring scorch heights and using them to back-calculate fireline intensity using Van Wagner's (1973, 1977) crown scorch model. Depth of burn/char measurements can be used to estimate residence time in surface fuels and soils. Wildland fuels are poor conductors of heat. Due to heat transfer constraints, fuels burn at relatively constant rates (Anderson 1969; Frandsen 1991a,b). A fire can be very intense, as exhibited by long flame lengths, but its duration within the forest strata most determines the depth of burn/char. Readers are referred to the recent review by Keeley (2009) for further discussion on the topic of fire intensity versus fire severity. A more in-depth discussion of the differences between fire intensity and fire severity can be found in the *Effects of Fire on Soil and Water* volume (Neary and others 2005), and Ryan 2002. Field guidance on determining fire severity may also be found in the appendix.

Integrating Fire Severity With Cultural Resources

In short fire return forests where duff accumulation is restricted, the burnout of CWD is the primary source of deep soil heating (Monsanto and Agee 2008). In forests with long fire return intervals, the buildup of duff covers most of the forest floor surface. Logs, even at high fuel loadings, rarely cover more than 10 percent of the soil surface area (Albini 1976; Brown and others 2003; Peterson and Ryan 1986). Thus, the most common source of deep soil heating is the burnout of the duff. Equations exist to predict duff consumption in the United States (Brown and others 1985, 1991; Ottmar and others 1993, 2005; Reinhardt 2003) and Canada (Chrosciewicz 1968, 1978a,b; de Groot and others 2009; Muraro 1975; Van Wagner 1972). Predictions are available using both actual measured moisture contents (fig. 2-16) or more readily available fire danger rating indices (figs. 2-17, 2-18). Users are referred to equations in the CONSUME (Ottmar and others 1993, 2005, accessed November 13, 2009) and FOFEM (Reinhardt 2003) publications as a means of predicting expected duff, FWD, and CWD consumption in wildfires or prescribed fires.

In addition to the burnout of duff and woody fuels, there are a number of other means by which buried cultural resources can be heated. One of the most common is the burnout of stumps and dead roots. Commonly at cultural sites, logs and building materials are buried

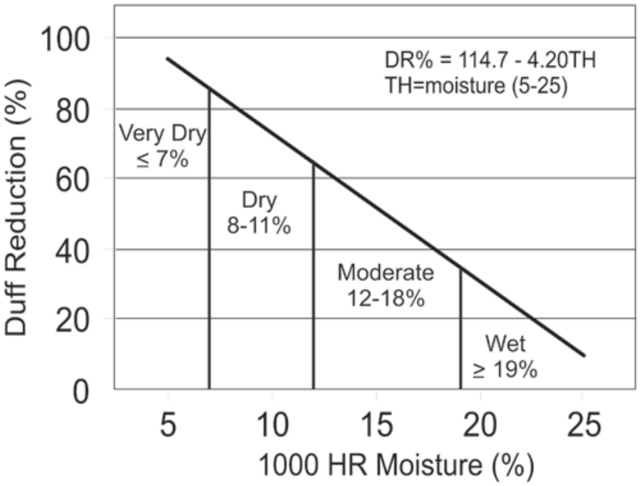

Figure 2-17—Illustration of duff consumption, percent of total duff available (%), as a function of U.S. National Fire Danger Rating System (NFDRS) (Deeming and others 1977) thousand hour moisture content for common forest conditions where duff is greater that 4 centimeters deep and able to burn independent of a surface fire if dry enough to burn (equation from Brown and others1985).

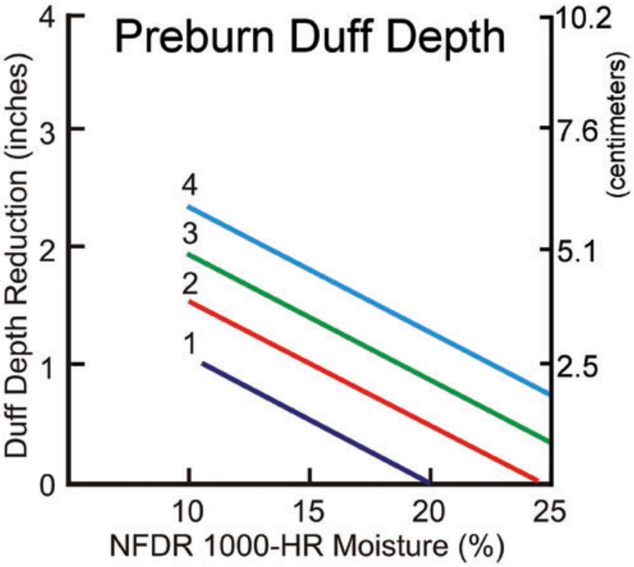

Figure 2-18—Illustration of duff depth reduction (in.) as a function of varying initial duff depths (in.) and U.S. National Fire Danger Rating System (NFDRS) (Deeming and others 1977) thousand hour moisture content based on Brown and others 1985. (1 in. = 2.54 cm.)

or partially buried. Once ignited these burn slowly, deeply heating lower layers in the soil profile. Another mode of subsurface heating is when soil is interspersed with organic material in old middens and dump sites where fire can freely move throughout the strata. For further discussion of these unique fire environments see chapters 6, 7 and 9.

The conceptual model of fire severity developed by Ryan and Noste (1985) defines severity as the union of the heat pulse above the site and the heat pulse in the ground (heat pulse up – heat pulse down) (appendix table A-3). As the mass of fine fuel increases, so does the potential for a high intensity surface fire or crown fire. The primary weather factors that determine how intensely that fine fuel mass will burn are the wind speed and short-term drying (i.e., low relative humidity). Canopy fuels readily torch at relative humidity less than 20 percent. As fire intensity increases, so does the above-ground heat pulse. Likewise, the potential for fire to damage surface and above-ground cultural resources also increases. The increased radiant flux associated with large flames more effectively heats surfaces at greater distances than is possible with small flames (see sidebar 2-1). Also, as fire intensity increases, fires become more uniformly severe as more surface and canopy fuel is consumed. As the depth of burn increases the potential to damage surface and sub surface resources increases. With greater depth of burn, more heat is released for a longer period of time and the distance between the combustion zone and a buried artifact is reduced as organic soil horizons are consumed. The primary factors determining the depth of burn are long-term drying and the depth of organic material available on the site (fig. 2-19). The primary factor determining the temperatures reached in the soil is the depth of burn whether resulting from increased duff consumption (fig. 2-20) or increased burnout of coarse woody debris (fig. 2-21). The depth of burn and the temperatures reached in the soil determine the damage to subsurface cultural resources.

In their work on classifying fire severity, Ryan and Noste (1985), Ryan (2002), and Neary and others (2005) stressed the concept that one needs to look independently at the heat pulse above the fire as well as the heat pulse in the ground. For practical reasons, it is often impossible to adequately instrument a site in order to get definitive measures of the energy release characteristics or temperature history across a burned area of interest. The spatial variability of fuels and fire behavior within most fires precludes actual quantification in most cases. Classification of the level of fire treatment has considerable pragmatic utility. While remote sensing of fire characteristics is becoming increasingly common (Kremens and others 2010; Lentile and others 2006, 2007, 2009) and real-time monitoring from remote platforms such as aircraft or satellites shows great promise for the future, most cultural resource specialists will have to rely on proxy data to reconstruct and classify the level of fire treatment associated with observed fire effects. In the case of unplanned fires, *ex post facto* measures are all that is available to ecologists and archaeologists alike. The fire severity matrix (appendix table A-3) describes a classification of fires in a 6 by 4 matrix with six classes of heat pulse above the ground and four classes of depth of burn including the unburned case. In addition, figures 2-16 through 2-21 can help inform burning prescriptions designed to manage the effects of fire on cultural resources during fuel reduction and ecosystem restoration treatments. Buenger (2003) presented data and synthesis of the effects of high temperatures on various archaeological and historically significant materials. Data are also presented on temperature effects on ceramics (chapter 3), lithics (chapter 4), and historic era materials (chapter 6) in this publication. Ryan (2010) summarized these temperatures and discussed the importance of the duration of exposure to high temperatures (sidebar 2-2). These temperatures can be compared to representative temperature histories of fires (e.g., figs. 2-8, 2-10, 2-11, 2-12, 2-14, 2-19, and 2-20) to bound expected fire effects when planning prescribed burns or post wildfire rehabilitation and stabilization.

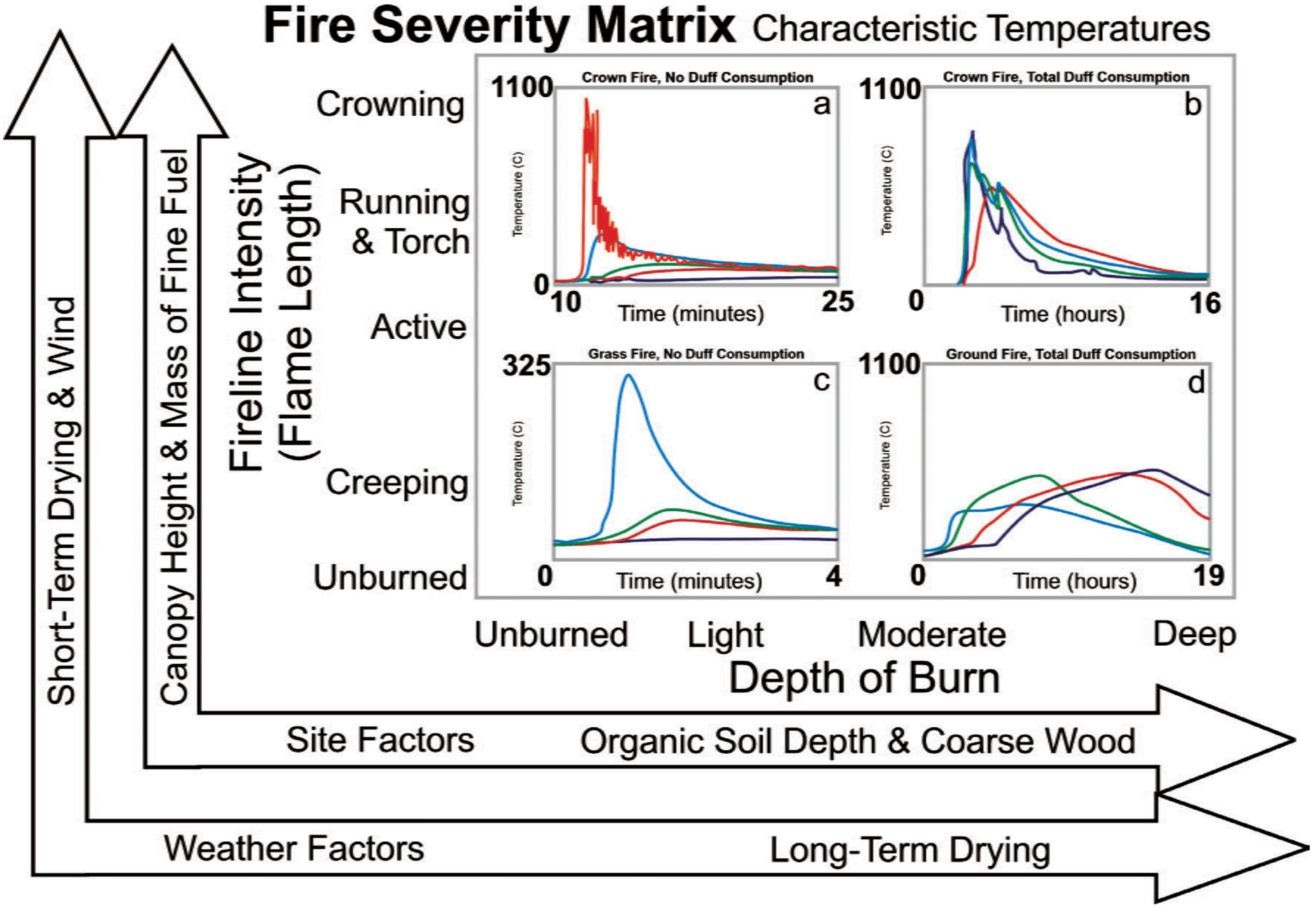

Figure 2-19—Representative temperature histories for fires of varying severity: (a) crownfire/low depth of burn (DOB), (b) crownfire/moderate DOB, (c) active surface fire/low DOB, (d) creeping surface fire/moderate DOB. (See text and appendix for fire intensity and DOB descriptions.) Differing combinations of high temperature and duration of heating lead to fires of different severity. Changes in site variables, including terrain and vegetative structure, and weather variables lead to fires of differing peak temperature and duration. Broad arrows indicate increasing site and weather potential. Both site and weather conditions must be met to affect fire severity (adapted from Ryan 2002).

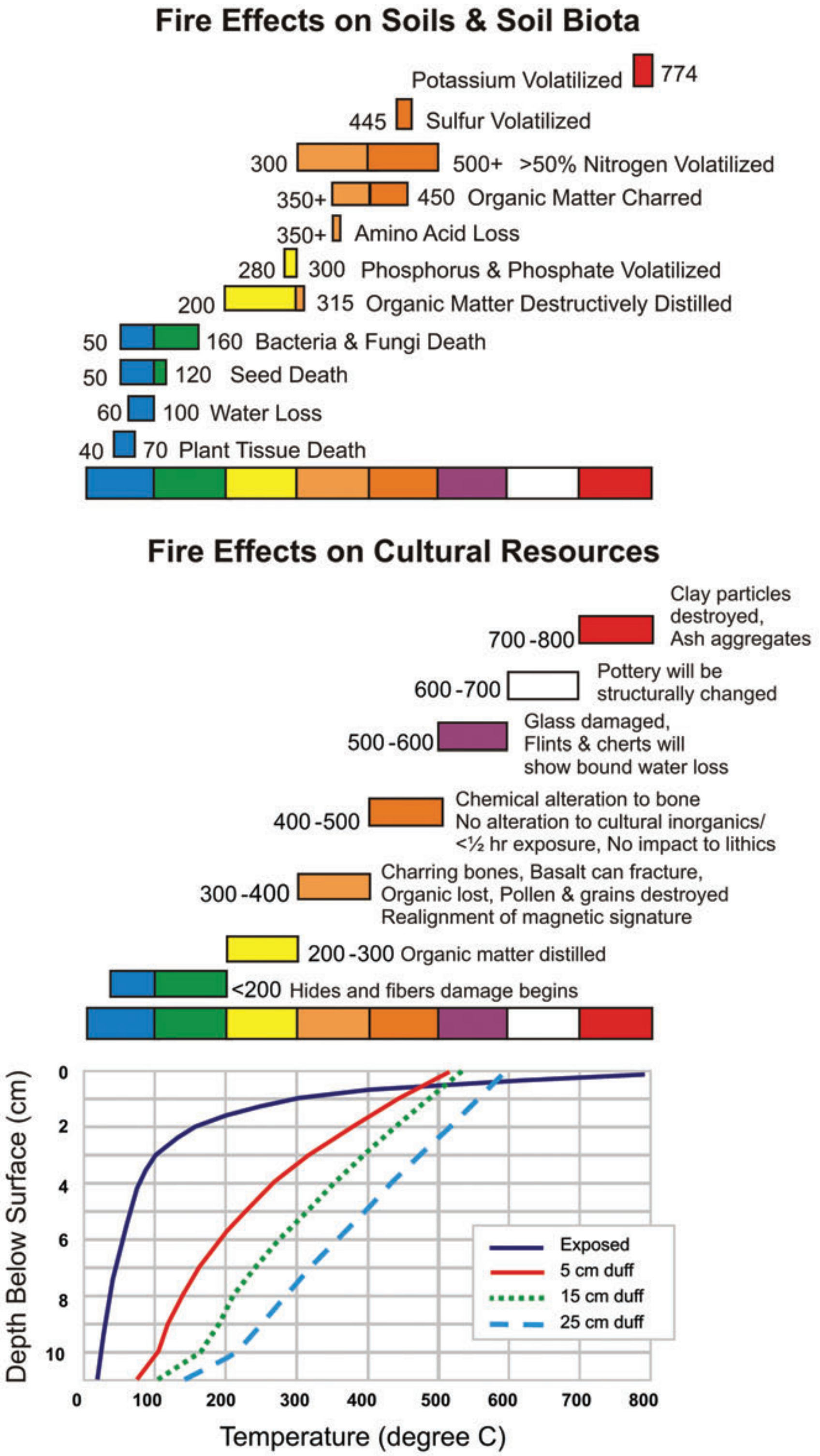

Figure 2-20—Temperature ranges associated with various biophysical fire effects (top) (modified from Hungerford and others 1991) and cultural resource fire effects (center) compared to the depth of heat penetration into mineral soil (bottom) for a crown fire over exposed mineral soil (observed in jack pine *Pinus banksiana* in the Canadian Northwest Territories) or for ground fire burning in 5-, 15-, and 25-cm of duff (predicted by Campbell and others1994, 1995). Conditions are for coarse dry soil, which provides the best conduction (i.e., a worst-case scenario) (adapted from Ryan 2002).

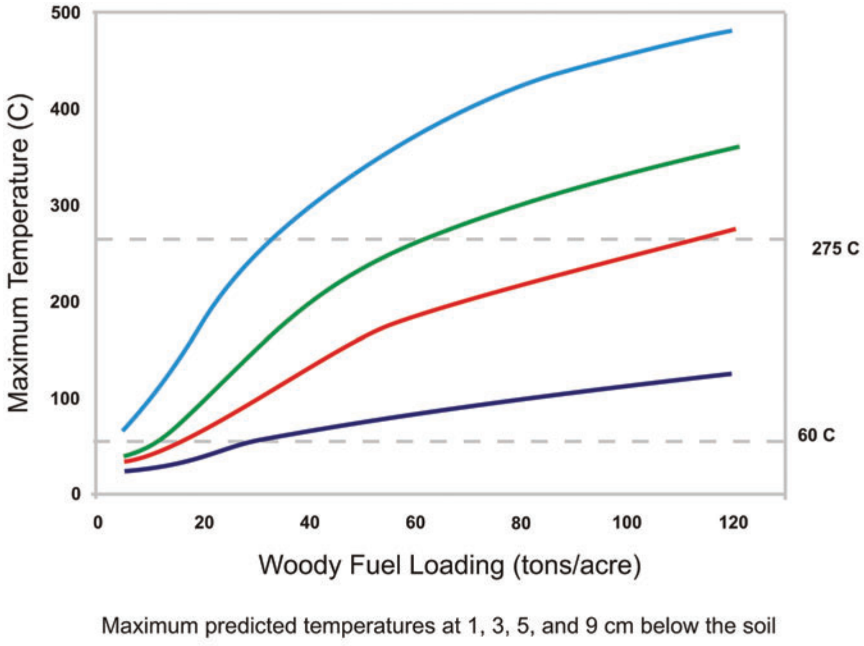

Figure 2-21—Maximum soil temperatures predicted by the soil heating model in the First Order Fire Effects Model (FOFEM) (Reinhardt and others 2005) for varying loadings of coarse woody debris (CWD (from Brown and others 2003). Solid lines depicting 1, 3, 5, and 9 cm below the soil starting from top to bottom.

Fire Regime

In current fire management, the highest spatial and temporal fire scale of interest is described by the fire regime (fig. 2-1). Scott (2000) refers to the paleo-fire triangle—an even higher scale represented by atmosphere, vegetation, and climate—which recognizes that terrain and atmospheric chemistry are variable over geologic time frames. This longer term perspective may not seem too relevant to fire managers; however, in the study of climate-vegetation-fire relationships that affected ancient cultures, it is germane to many reconstructions of archaeological information. Understanding climate-vegetation-fire interactions is likely to become of greater importance in formulating future fuels treatment and restoration policies under climate change scenarios (Lovejoy and Hannah 2005).

Fire regime concepts emerged in the fire ecology literature with the early work of Heinselman (1978, 1981) and Kilgore (1981). In recent years there has been considerable refinement in fire regime concepts as ecologists have investigated more ecosystems and have developed a greater appreciation for how fire regimes vary over time. At the same time, ecological theory has matured to recognize the importance of periodic disturbance to the maintenance of ecological integrity (Agee 1993; Hardy and others 2001; Morgan and others 2001; Sugihara and others 2006). In the United States, the use of fire regime concepts has increasingly been used in the fire ecology and management communities, particularly in the context of the Coarse-Scale Assessment of Fire Regime Condition Class (FRCC) (Schmidt and others 2002) (table 2-4) and because its use is mandated under the Healthy Forests Restoration Act of 2003 (H.R. 1904). Fire regime refers to the general nature of the type of fire that most commonly occurred over long time periods (Agee 1993; Brown 2000; Hardy and others 1998; Sugihara and others 2006).

Table 2-4—Historical natural fire regimes from Coarse-Scale Assessment of Fire Regime Condition Class (Schmidt and others 2001).

Code	Description
I	0-35 year frequency[a], low severity[b]
II	0-35 year frequency, stand replacement severity
III	35-100+ year frequency, mixed severity
IV	35-100+ year frequency, stand replacement severity
V	200+ year frequency, stand replacement severity

[a] Fire frequency is the average number of years between fires.
[b] Severity is the effect of the fire on the dominant overstory vegetation.

Sidebar 2-2—Impact of Temperature and Duration of Heating on Lithics

It is common knowledge that many material transitions occur as complex functions of temperature and duration of exposure. Such functions are often described by Arrhenius functions (fig. S-2.1) (Ryan 2010). Few time-temperature data are available (e.g., Bennett and Kunzman 1985; Buenger 2003), and those that do exist are not robust enough to calculate actual Arrhenius functions but they are adequate to illustrate their potential use. The following example uses data from Bennett and Kunzman (1985) to illustrate the principle. (Bennett and Kunzman's work is unpublished but widely cited and sometimes misinterpreted because the results of laboratory muffle furnace results are difficult to extrapolate to field burning situations.)

General Information:

- Type of research: Laboratory experiment
- Purpose: Heating experiment was designed to mimic a range of wildland fire situations
- Experimental heating of artifacts conducted by Bennett and Kunzman, Western Archeological and Conservation Center, National Park Service, Tucson, Arizona
- Heating description:
  - Temperature range: 200 to 800 °C (392 to 1472 ºF)
  - Duration: 3,000,000 degree-minutes for temperatures between 200 and 600 °C (392 and 1112 ºF); 1,345,000 and 1,400,000 degree-minutes for two trial runs of 800 °C (1472 ºF) max temperature.
- Equipment used:
  - Electric thermolyne-type 1400 muffle furnace; temperature measured by a Weelco controller
  - Temperatures of heated specimens measured by 36 gauge iron-constantan (type J) thermocouples
  - Perkin Elmer 599 infra-red spectrometer used to measure bound water loss

Procedures:

Peter Bennett and Michael Kunzmann (1985) conducted experimental heating of artifacts in the materials and ecological testing laboratory of the Western Archeological and Conservation Center in Tucson, Arizona. They used a muffle furnace to assess potential damage to artifacts heated at prescribed burn temperatures. In their experiments, Bennet and Kunzman examined specimens of chert, flint, chalcedony, obsidian, prehistoric earthenware, and historic to modern bone, glass and enameled tinware. Separate samples of specimens were heated in the furnace to different maximum temperatures. Duration of heating was measured in degree-minutes. Degree-minutes of heating were equal to the maximum temperature reached minus 100 °C (212 ºF) multiplied by the time in minutes: (max. temp. – 100 °C (212 ºF)) (minutes heated). Duration of heating in degree-minutes was generally kept standard.

Color change and other visual alterations to the surface of items were recorded. Heating effects to artifact structure were identified in terms of chemically bound water loss and weight loss due to causes other than evaporation of free water. Free water evaporation was measured by heating specimens in a drying oven at 100 °C (212 ºF). Loss of chemically bound water was determined with the use of an infrared spectrometer on ground-up pieces of specimens before and after furnace heating. Weight loss not accounted for by free or bound water loss was attributed to other causes.

Specimens were also heated and plunged into cold water to test for thermal shock. The rate of cooling in water was judged to be greater than 500 °C (932 ºF) per minute. Although this test was not carefully controlled, a minimal amount of observed cracking and spalling led Bennett and Kunzman to conclude that thermal shock was not a major concern in prescribed burns.

Given estimates of the Arrhenius functions for various cultural materials provide a means to compare expected temperatures and durations of fires to assess the likelihood of CR damage. Such assessments require applying knowledge of the CR material type and its location (for example, exposed above ground versus insulated by unburnable mineral soil), the combustion characteristics of nearby fuels, and the heat transfer mechanisms coupling fire behavior to the CR. In practice, many cultural materials including lithics are composed of various elements, often in layers, and each with their own thermal properties. Rapid heating or cooling can create internal stresses that cause materials to fracture (e.g., potlidding, spalling). Such mechanical failures are difficult to explain with Arrhenius functions; however, time-temperature relationships help to explain why an artifact of a given material type might display similar damage over a range of fire behaviors. Likewise, they help explain why two different material types might display very different effects from a given fire behavior.

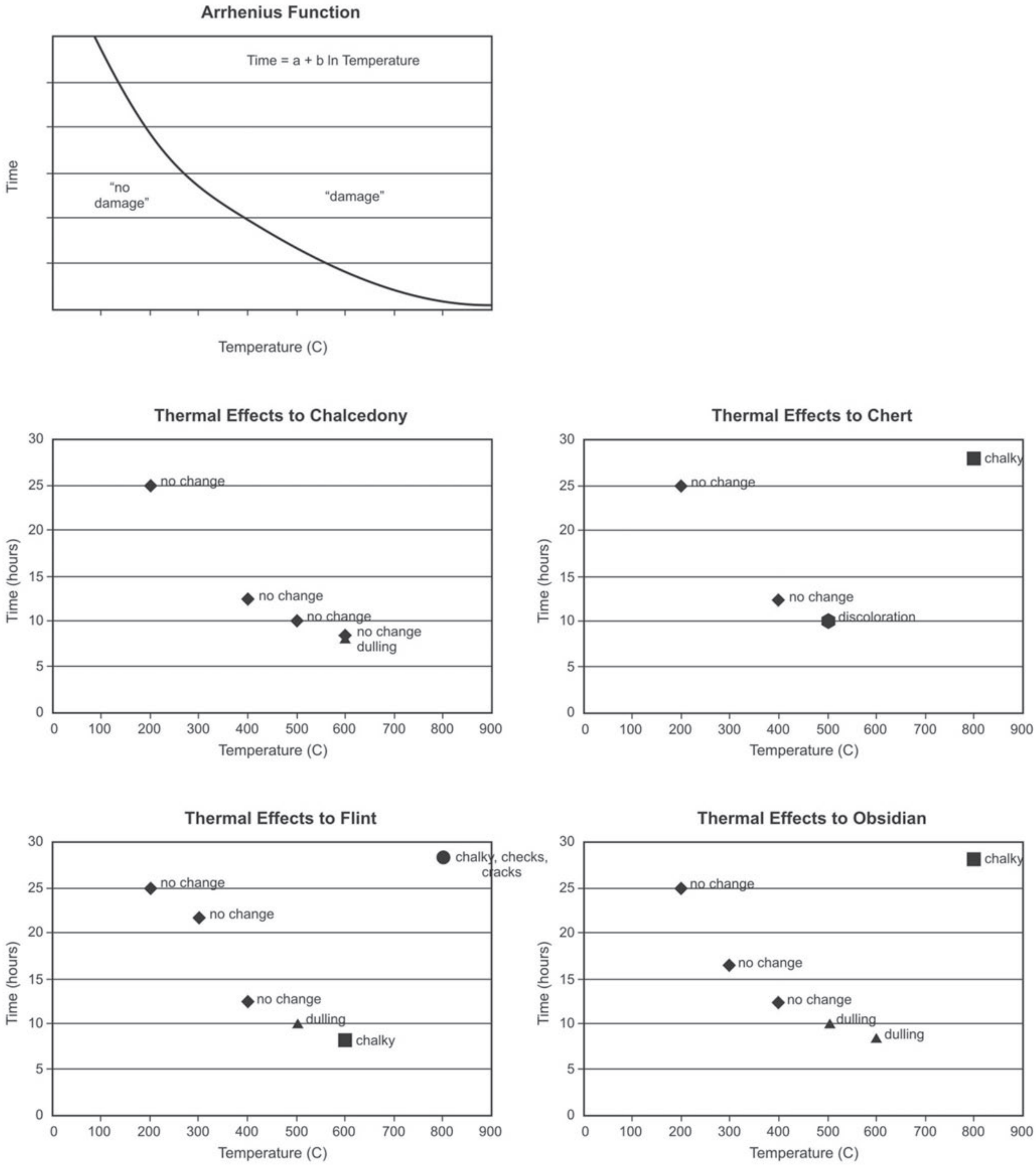

Figure S2.1. Time-temperature relationships for four lithic materials (from Bennett and Kunzman 1985).

The actual terms used and the concepts they describe vary somewhat and this can result in confusion. Fire regimes include descriptions of the frequency and severity of the fire. Older literature often referred to the effects of the fire as **intensity** but common usage in current North American literature favors the term **fire severity** as a description of the effects of fire (Agee 1993; Brown 2000; Hardy and others 1998; Keeley 2009; Neary and others 2005; Ryan 2002). Readers are referred to the *Effects of Fire on Flora* (Brown 2000) for a description of various early uses of the fire regime concept. There is a large body of more recent fire regime-related literature, the review of which is beyond the scope of this chapter. Interested readers are invited to type the words "fire regime" into their favorite internet search engine.

The following terms are commonly encountered in the fire regime literature. **Understory fire regime**, **surface fire regime**, **low severity fire regime**, and **non-lethal fire regime** are terms used to describe fires that are generally non-lethal to the dominant vegetation and do not substantially change the structure of the dominant vegetation (Brown 2000). Such descriptions apply to forests and woodlands. As originally defined by Brown (2000), approximately 80 percent or more of the dominant vegetation must survive to be deemed non-lethal. In the FRCC field methods used by Federal land management agencies in the United States, the cut-off is 75 percent or more (Hann and Bunnell 2001). In either case, most of the dominant arboreal vegetation survives. A **stand replacement fire** or **lethal regime** is one that either consumes or kills 80 percent or more of the above-ground dominant vegetation (Brown 2000), or 75 percent or more according to FRCC field methods (http://www.frcc.gov) (Hann and Bunnell 2001). Stand replacement fire regimes apply to forests, woodlands, shrublands, and grasslands (Brown 2000). In the case of grasslands, the post-fire community often recovers quickly from surviving meristematic tissues, such as rhizomes and bulbs. Intermediate regimes, or those between understory and stand replacement fire regimes, are generally referred to as **mixed severity fire regimes.** Mixed severity fire regimes can occur due to variation in space or time. However, some forest types tend to go through cycles wherein the series of low severity fires is periodically punctuated with stand replacement fires as long-term climate trends oscillate between warm-dry and cool-moist climate periods. Brown (2000) and several other authors also recognize a non-fire regime where there is little or no occurrence of natural fire. This description may be useful in discussions of vegetation types where fire is rare. However, upon close inspection, evidence of past fires is found in virtually all non-marine vegetation types (Andreae 1991; Bond and others 2005; Clark and others 1997; Delacourt and Delacourt 1997; Levine 1991; Levine and others 1995, 1996a,b; Power and others 2008). Determining whether or not these fires are natural or were started by aboriginal people is often problematic (Anderson 2005; Barrett and Arno 1982; Bonnicksen 2000; Boyd 1999; Denevan 1992; Vale 2002). Throughout the period of human occupation of North America, aboriginal people are widely believed to have extensively burned the landscape (Bonnicksen 2000; Boyd 1999; Delacourt and Delacourt 1997; Delacourt and others 1998; Erickson 2008; Gavin and others 2007; Hallett and others 2003; Jurney and others 2004; Kay 1994, 1998, 2007a,b; Keeley 2002; Leenhouts 1998; Lewis 1989; Moore 1972; Nevle and Bird 2008; Pausas and Keeley 2009; Stewart 1956, 1982; Williams 2000). Use of fire by aboriginal people was pervasive (Anderson 2005; Barrett and Arno 1982; Boyd 1999; Kay 1994; Denevan 1992; Kay and Simmons 2002; Williams 2000). Infrequent fires can have long-lasting effects on species composition and stand structure (Brown and others 1999; Frost 1998; Kaufmann and others 2000, 2004).

Fire Planning

The careful planning and implementation of fuel treatment or restoration projects can go a long way toward minimizing the potential impacts on cultural resources (see chapter 9). Well executed projects can greatly reduce the impacts of subsequent wildfires. Also integrating fire behavior and effects concepts with an understanding of how cultural resources are impacted by fire (fig. 2-20) can aid in the planning and implementation of post-fire restoration and monitoring.

Planning fuels treatments, restoration projects, or suppression activities requires that cultural resource specialists collaboratively plan activities with fire management personnel (see chapter 9). In addition to the graphical aids in this chapter (figs. 2-15 through 2-21), there are numerous software decision support tools, databases, and syntheses available to resource professionals. There are a number of agency-developed software programs that can be used to predict fire behavior and to project probable effects at both the site and landscape levels. These predictive tools, used by managers to support planning and decisions, vary in their inputs, outputs, and uses. The following discussion identifies a few commonly used by the fire management community. For more information please visit http://fire.org, the Fire Research and Management Exchange System (FRAMES, http://frames.nbii.gov/portal/server.pt), or use an internet search engine to search each program individually. Additional resources are listed in table 2-5.

Table 2-5—Annotated list of fire effects resources for planning and evaluating fuel treatment and restoration projects and surveying and monitoring wildland fire management activities (adapted and modified from Kelly Pohl, TNC Global Fire Initiative, LANDFIRE Program).

Resource/Tool	Description	Type of tool		
		Fire ecology resource	Resource search	Monitoring/ Modeling
Smith, J.K., ed. 2000. **Wildland fire in ecosystems: effects of fire on fauna**. http://www.treesearch.fs.fed.us/pubs/4553	A volume from the Rainbow Series that outlines the effects of fire on North American fauna.	X		
Brown, J.K.; Smith, J.K., eds. 2000. **Wildland fire in ecosystems: effects of fire on flora**. http://www.treesearch.fs.fed.us/pubs/4554	A volume of the Rainbow Series that outlines historical and current fire regimes and fire effects organized by Kuchler Natural Potential Vegetation Types.	X		
Neary, D.G.; Ryan, K.C.; DeBano, L.F., eds. 2005. **Wildland fire in ecosystems: effects of fire on soil and water**. http://www.treesearch.fs.fed.us/pubs/20912	A volume from the Rainbow Series that outlines the effects of soil and water. The volume: 1) defines fire severity as it affects soil and water resources, 2) synthesizes the state of knowledge on the effects of fire on the physical, chemical and biological properties of soil; and water quality; and 3) summarizes erosion models and burned area rehabilitation practices	X		
Sandberg, D.V.; Ottmar, R.D.; Peterson, J.C.; Core, J. 2002. **Wildland fire in ecosystems: the effects of fire on air**. http://www.treesearch.fs.fed.us/pubs/5247	A volume from the Rainbow Series that outlines the effects of fire on air quality to assist managers with smoke planning.	X		
Zouhar, K.; Smith, J.K.; Sutherland, S.; Brooks, M.L. 2008. **Wildland fire in ecosystems: fire and non-native invasive plants**. http://www.treesearch.fs.fed.us/pubs/30622	A volume from the Rainbow Series that outlines the effects of fire on exotic and invasive weeds	X		
Grissino-Mayer, H.D. 2003. **Dendrochronology Literature Database** http://www.waldwissen.net/themen/wald_gesellschaft/forstgeschichte/wsl_jahrringforschung_datenbank_EN	A searchable database of tree-ring literature, including many fire history studies. This literature can provide information about fire effects, fire history, fire regimes, and disturbance interactions, among other topics.		X	
ESSA Technologies Ltd. **TELSA: Tool for Exploratory Landscape Scenario Analysis.** http://www.essa.com/tools/telsa/index.html	A spatially explicit, landscape-level model of forest dynamics to help assess the consequences of alternative management scenarios. Used with VDDT and ArcView 3.X. Software and training are available upon request.			X
ESSA Technologies Ltd. **VDDT: Vegetation Dynamics Development Tool.** http://www.essa.com/tools/vddt/index.html	Public domain state-transition modeling software that provides functions for natural vegetation succession and natural and human disturbances. Resulting models can help create estimates of percent cover for different vegetation types (states) and important drivers in landscape change (transitions). Models are not spatially explicit and do not account for biophysical constraints.			X

Table 2-5—Continued

Resource/Tool	Description	Type of tool		
		Fire ecology resource	Resource search	Monitoring/ Modeling
U.S. Department of Agriculture **Fire Effects Information System (FEIS)** http://www.fs.fed.us/database/feis/	A complete database of the effects of fire on plant and wildlife species and communities in North America, searchable by species or Kuchler Potential Natural Vegetation Type. Contains sections on distribution, botanical and ecological characteristics, succession, fire ecology and effects, management considerations, and case studies.	X		
U.S. Department of Agriculture **Fire Effects Information System (FEIS) Citation Reference System (CRS)** http://www.feis-crs.org/	A searchable database of all of the references cited in the Fire Effects Information System (FEIS). Searchable by subject, year, author, or any combination thereof. A complete fire history literature database!		X	
U.S. Department of Agriculture & The Nature Conservancy **Fire Regime Condition Class Guidebook and Reference Conditions** http://www.frcc.gov	A standardized, interagency protocol for assessing the departure of current conditions from historical reference conditions. Information and methodology are available at the web address listed. National training events are held regularly. Reference Conditions for potential natural vegetation groups across the U.S. are described, including reference mean fire intervals and successional stages.	X		X
The Northwest and Alaska Fire Research Clearinghouse. **FIREhouse** http://depts.washington.edu/nwfire/	A web-based data center providing documentation and data on fire science and technology relevant to Washington, Oregon, Idaho, and Alaska.		X	
Fire Sciences Laboratory **FIREMON: Fire Effects Monitoring Protocol** http://frames.nbii.gov/firemon	Sampling protocol, sources, and forms for determining current conditions. Methodologies can be used directly or serve as templates.			X
FRAMES: Fire Research and Management Exchange System http://frames.nbii.gov/portal/server.pt	A suite of software developed for fire management professionals, including modeling programs like BEHAVE and FARSITE. Also an information exchange with bulletin boards and notice pages that facilitate collaboration among fire management professionals.			X
Interagency Research Partnership **Joint Fire Sciences Program** http://www.firescience.gov/	The Joint Fire Science Program (JFSP) funds research and development projects focused on improving the knowledge available for management and policy decisions to support federal, tribal, state, and local agencies and their partners. JFSP provides access to reports of past projects and links to related sites.	X	X	
U.S. Department of Agriculture, U.S. Geological Society, The Nature Conservancy, U.S. Department of the Interior **LANDFIRE** http://www.landfire.gov	LANDFIRE is a wildland fire, ecosystem, and fuel assessment-mapping project designed to generate consistent, comprehensive, landscape-scale maps of vegetation, fire, and fuel characteristics for the United States.	X		X

Table 2-5—Continued

Resource/Tool	Description	Type of tool Fire ecology resource	 Resource search	 Monitoring/ Modeling
Systems for Environmental Management **Fire.org: Public Domain Software for the Wildland Fire Community** http://www.fire.org/	Systems for Environmental Management provides downloadable versions of public domain software for predicting fire weather, behavior, and effects ass well as links to other sources of fire information.			X
Schmidt, K.M.; Menakis, J.P.; Hardy, C.C.; Hann, W.J.; Bunnell, D.L. 2002. **Development of coarse-scale spatial data for wildland fire and fuel management.** http://www.treesearch.fs.fed.us/pubs/4590	A national-scale mapping of fire regime data, including potential natural vegetation groups, current cover types, and historical and current fire regime condition classes. GIS data layers are available. Note that this data is at ecoregional scales and not suitable for project scale.	X		
Tall Timbers Research Station and Land Conservancy **Tall Timbers Library** http://www.talltimbers.org/info-library.html	A searchable database of literature on fire ecology, prescribed fire use, and control of fires. Has an international scope with a focus on the southeastern U.S.		X	
The Nature Conservancy **Global Fire Initiative** http://www.tncfire.org/training_landfire_techTransfer.htm	A resources site that describes how to use the ESSA VVDT successional models in the LANDFIRE Vegetation Model Library, and contains many other fire resources designed to help land managers.	X	X	X
Forest Service Research and Development **Treesearch** http://www.treesearch.fs.fed.us/	A searchable database of all USDA Forest Service publications online. Searchable by author, year, and region.		X	
USDA Natural Resources Conservation Service **The PLANTS Database** http://plants.usda.gov/index.html	A comprehensive database that provides standardized information on the vascular plants, mosses, liverworts, hornworts, and lichens of the US and its territories. PLANTS includes names, photos, checklists, and automated tools.			X
USDI National Park Service **National Park Service Fire Monitoring Handbook** http://www.nps.gov/fire/download/fir_eco_FEMHandbook2003.pdf	Outlining the National Park Service's standardized fire effects monitoring protocol, including setting goals and objectives, designing pre- and post-burn sampling, and data analysis. Also includes useful field forms, checklists, and additional reading lists.			X
Wildland Fire Lessons Learned Center http://www.wildfirelessons.net/	A web-based clearinghouse of information, case studies, and lessons learned to improve performance, safety, efficiency, and organizational learning in the interagency wildland fire community.		X	
Gassaway, L. **Fire Archaeology** http://web.mac.com/linnog/Fire_Arch/Home.html	A site designed to "disseminate information on the effects of fire to cultural resources, both historic and prehistoric." Includes information on protection, policy, and management.	X		
Federal Preservation Institute **Historic Preservation Learning Portal** https://www.historicpreservation.gov/web/guest/home	Portal with information in the field of historic preservation that covers and allows users to search for laws, policies, literature, news, case studies, training, and best practices.	X	X	

Fire Planning Software

Behave-Plus, v 5.0 (Andrews 2008; Heinsch and Andrews 2010) predicts wildland fire behavior for fire management purposes. Behave-Plus is used for real-time fire prediction of fire behavior on a specific site for a specific set of burning conditions, and as a treatment planning tool. This software uses the minimum amount of site-specific input data to predict fire for a given point in time and space. Behave-Plus is useful for gaming a proposed treatment by allowing users to quickly test the effect of changes in fuel moisture, wind, and fuel loading on predicted fire behavior and effects, thereby allowing the user to hone in on a favorable prescription window.

FARSITE (Finney 1998) is a landscape-level fire growth simulation model for forecasting fire growth and intensity and requires the input of topography, fuels, and weather and wind files. This software incorporates existing models for surface fire, crown fire, spotting, post-frontal combustion, and fire acceleration in a two-dimensional fire growth model. It was developed initially as a tool for managing fires in wilderness areas where fire often burns for several weeks. FARSITE was developed to predict how far a fire could spread over long periods of time under changing fire environment (fuels, terrain, and weather). Thus it requires landscape maps of fuels and terrain along with predicted weather over the simulation period. In the modeling framework, fuels are digital representations of fuel-bed properties using either the Anderson 13 fire behavior fuel models (Anderson 1982), the 40 Scott and Burgan fuel models (Scott and Burgan 2005), or user-defined custom fuel models (Burgan and Rothermel 1984). While FARSITE does not explicitly require fuels data at any particular spatial resolution, analyses are typically at 30-meter pixel (900 m^2) (0.22 acre). This spatial resolution is based on analysis of readily available LANDSAT TM-7 data. In the United States, FARSITE fuel and vegetation inputs are freely available through the standardized LANDFIRE national data product (www.landfire.gov) (Rollins 2009; Reeves and others 2009; Rollins and others 2006; Ryan and others 2006). Digital terrain is routinely available from a variety of sources (e.g., USGS), including LANDFIRE. Weather input is provided by the user either from predicted weather or historic climate/weather data. FARSITE is spatially explicit and predicts fire spread and intensity for every place on the perimeter at every time step. Thus, as fires grow in size the model becomes increasingly computationally intensive. Guidance for inputting fuels data and analyzing potential fire behavior are contained in Stratton (2006).

FlamMap is a related model that looks at the spatial pattern of fire potential under static, user-defined weather conditions. Thus it is useful for determining the fire potential in the vicinity of infrastructure (Cohen 2000), natural resources, and cultural resource sites. FlamMap creates raster maps of potential fire behavior characteristics (spread rate, flame length, and crown fire activity) and environmental conditions (dead fuel moisture, mid-flame wind speeds, and solar irradiance) over the entire landscape. Unlike FARSITE, there is no temporal component in FlamMap although they use the same spatial and tabular data as input. This input includes a landscape file, initial fuel moistures, custom fuel models, as well as optional conversion weather and wind files. Many fire behavior models are incorporated into FlamMap ranging from Rothermel's 1972 surface fire spread model to Nelson's 2000 fuel moisture model. In addition to technical knowledge of fire, FARSITE and FlamMap may require geographic information system analyst assistance to obtain spatial landscape information for input to the program.

FireFamily Plus, v.4 (http://www.firemodels.org/index.php/national-systems/firefamilyplus, accessed May 5, 2011) is a software package that quickly summarizes historic weather patterns for local management planning in the United States. Fire Family Plus combines fire climatology and occurrence analysis capabilities of the PCFIRDAT, PCSEASON, FIRES and CLIMATOLOGY programs into a single package with a graphical user interface. This software package is valuable for designing burning prescriptions that are operationally feasible by letting the user determine the frequency and timing of suitable burning weather. In particular, users can analyze historic drying trends critical for achieving cultural resource objectives in prescribed burns.

NEXUS, v. 2.0 (Scott and Reinhardt 2001) is crown fire hazard analysis software that links to separate models of surface and crown fire behavior to compute relative crown fire potential. This software is used to compare crown fire potential for different stands and compare the effects of alternative fuel treatments on crown fire potential. NEXUS updated its previous model from an Excel spreadsheet to a stand-alone program in 2003. The information may be combined with other program output in the future to better understand crown fire development and behavior. Operators of this program should be familiar with BehavePlus (Andrews 2008; Heinsch and Andrews 2010) and be familiar with crown modeling techniques to fully comprehend the simulations in NEXUS and their respective meanings.

Behave Plus, FARSITE, and FlamMap are all meant for users trained in fire planning, behavior, and effects. This group of users should be familiar with fuels, weather, topography, wildfire situations, and associated concepts and terminology. Use of these programs is strictly intended to provide information to trained professionals to make educated land and fire management decisions.

Prometheus, v. 5.3 (http://www.firegrowthmodel.com/) is a deterministic fire growth simulation model (Tymstra and others 2010). It uses spatial fire behavior input data on topography (slope, aspect, and elevation) and Canadian Forest Fire Behavior Prediction (FBP) System fuel types, along with weather stream and FBP fuel type lookup table files. Prometheus uses the simple ellipse as the underlying template to shape fire growth, and simulates fire growth using the Canadian Forest Fire Danger Rating System (CFFDRS)—Fire Weather Index (FWI) and Fire FBP Sub-Systems—to model fire behavior outputs. It uses Grid ASCII, Generate files, and Shapefiles. Prometheus is a national interagency project endorsed by the Canadian Interagency Forest Fire Centre (CIFFC) and its members.

The Canadian Forest Fire Behavior Prediction (FBP) System (http://cwfis.cfs.nrcan.gc.ca/en_CA/background/summary/fbp, accessed February 5, 2010) (Hirsch 1996) provides quantitative estimates of potential head fire spread rate (ROS), total fuel consumption, and fire intensity. With the aid of the Prometheus elliptical fire growth model, it gives estimates of fire area, perimeter, perimeter growth rate, and flank and back fire behavior. Descriptions of the primary outputs follow:

1. **Rate of Spread** (**ROS**) is the predicted speed of the fire at the front or head of the fire (where the fire moves fastest). It takes into account both crowning and spotting and is measured in meters per minute based on the Fuel Type (FT), Initial Spread Index (ISI), Buildup Index (BUI), and several fuel-specific parameters, such as phenological state (leafless or green) in deciduous trees, crown base height in coniferous trees, and percent curing in grasses.
2. **Total Fuel Consumption (TFC)** is the predicted weight of fuel consumed by the fire both on the forest floor and in the crowns of the trees. It is measured in kilograms per square meter of ground surface and is based on Foliar Moisture Content (FMC), Surface Fuel Consumption (SFC), and ROS.
3. **Head Fire Intensity (HFI)** is the predicted intensity, or energy output, of the fire at the front or head of the fire. This is one of the standard gauges by which fire managers estimate the difficulty of controlling a fire and select appropriate suppression methods. It is measured in kilowatts per meter of fire front and is based on the ROS and TFC.
4. **Crown Fraction Burned (CFB)** is the predicted fraction of the tree crowns consumed by the fire based on BUI, FMC, SFC, and ROS.
5. **Fire Type (FT)** is a general description of the fire based on the CFB.

The First Order Fire Effects Model (FOFEM) (http://frames.nacse.org/0/939.html, accessed May 5, 2011) (Reinhardt 2003) is used by managers and planners to predict and plan for fire effects. FOFEM is used for impact assessment and for long range planning and policy development; it helps quantify predictions needed for planning prescribed fires that best accomplish resource needs. FOFEM inputs are divided into four geographic regions of the United States, thereby adding resolution through built-in forest cover types. Outputs include tree mortality; smoke emissions; consumption of duff, FWD, and CWD; mineral soil exposure; and soil heating. Users refer to FOFEM output to set upper and lower fuel moisture limits when writing prescriptions for conducting prescribed burns to manage vegetation injury and particulate emissions from a projected fire area. FOFEM can also be used to assess the effects of wildfire. This information is potentially valuable for designing post-fire surveys and rehabilitation projects. The list of output variables are (1) fuel consumption (percent consumption for these components: fine woody, coarse woody, and duff); (2) smoke (kg km^2 for these emission classes: PM2.5, CO^2, CH$_4$, and NO$_x$); (3) tree mortality (% mortality); and (4) soil heating (e.g., depth in cm at which temperature is 60 °C (140 °F) for 1 min (lethal) or 275 °C (527 °F) (irreversible damage to organics)).

Consume, v. 3.1 (http://www.fs.fed.us/pnw/fera/research/smoke/consume/consume30_users_guide.pdf, assessed May 5, 2011), (Ottmar and others 2007) predicts the amount of fuel consumption and emissions from burning logged units, piled debris, and natural fuels. The required inputs include weather data, the amount and moisture content of fuels, and other factors. Resource managers can accurately determine when and where to conduct prescribed burns to achieve desired objectives while reducing impacts on other resources. This software may be used for most forests, shrubs and grasslands in North America (adapted from abstract from Consume 2.0 user guide).

Weather is the most variable element in the fire environment. While antecedent and current weather are the primary considerations for predicting or documenting the direct effects of a specific fire on cultural resources, climate analyses are important for planning fuel treatment and restoration projects (Cerdà and Robichaud 2009; Neary and others 2005; Pannkuk and others 2000; Robichaud and others 2007) as well as in assessing the potential impacts of a fire on subsequent erosion (Johnson 2004a,b). Post-fire erosion often poses a greater threat to cultural resources than the direct effects of heat and smoke. The potential for post-fire erosion increases with increasing fire severity (Cerdà and Robichaud 2009; Neary and others 2005; Robichaud and others 2007) (fig. 2-22).

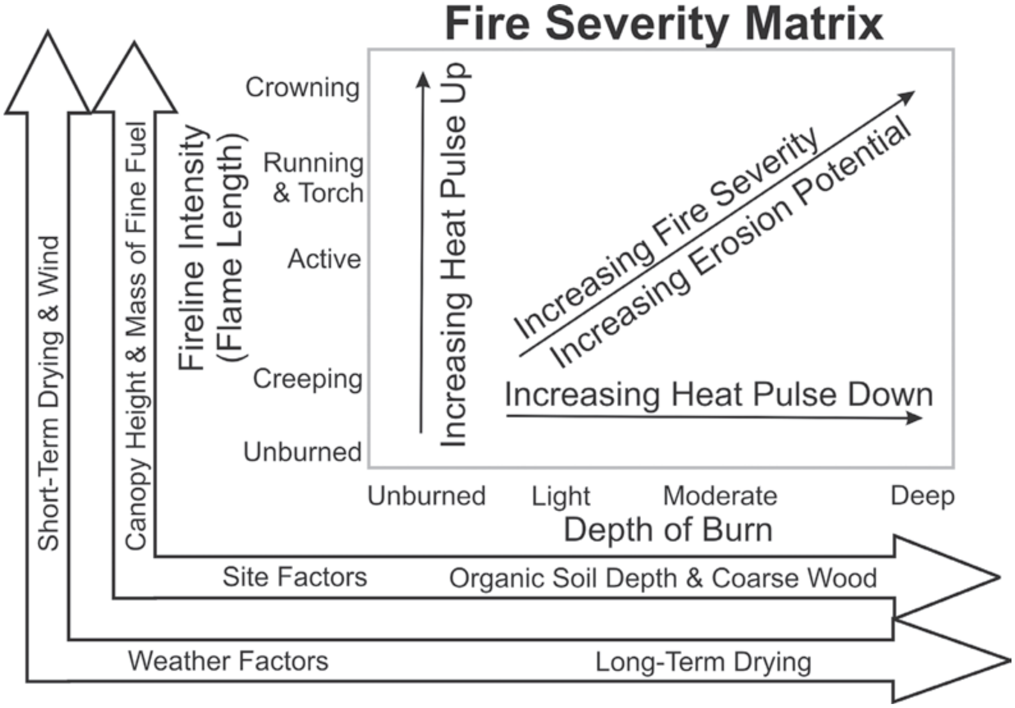

Figure 2-22—Site and weather factors associated with increasing fire severity and erosion potential. Increasing erosion potential increases the risk of damage to cultural resources (from Neary and others 2005).

Basic knowledge of climate, particularly seasonal patterns, can be used within shorter term weather forecasting to refine management prescriptions (Bowman and others 2009; Brown and others 2005; Heyerdahl and others 2008; Kitzberger and others 2007; Littell and others 2009; Morgan and others 2008; Preisler and Westerling 2007; Skinner and others 2006; Swetnam and Betancourt 1990, 1998; Trouet and others 2009; Wang and others 2010; Westerling and others 2006). Climate models are used for a variety of purposes, from study of the dynamics of the weather and climate system to projections of future climate.

Major recognized weather patterns include the North Atlantic Oscillation (NAO) (Ambaum and others 2001); the Northern Annular Mode (NAM) (McAfee and Russell 2008), (http://www.atmos.colostate.edu/ao/introduction.html, assessed May 5, 2011); the Arctic Oscillation (AO); Madden-Julian 30 to 60 Day Intra-seasonal Oscillation (MJO); The Indian Ocean Dipole (IOD), which is linked to the 3- to 7-year El Niño-Southern Oscillation (ENSO) (Izumo and others 2010; Kurtzman and Scanlon 2007); the Pacific Decadal Oscillation (PDO) with a 20- to 30-year oscillation (MantuPachauria 2002); a 20- to 40-year Atlantic Multi-decadal Oscillation (AMO); and the Interdecadal Pacific Oscillation (IPO) with a 15- to 30-year cycle. As climatologists improve our understanding of global circulation patterns, recognized patterns emerge. These patterns, referred to as teleconnections (Dixon and others 2008; Heyerdahl and others 2008), identify lags between ocean and atmospheric measurements and subsequent probable weather in various parts of the globe. These teleconnections are improving our ability to predict fire potential for fire planning purposes.

Climate, vegetation/fuels, and fire are dynamically coupled (fig. 2-1); any change in one will lead to changes in the others (Ryan 1991) with numerous inherent feedbacks (Running 2008). There is near universal agreement in the science community that anthropogenic activities—principally the burning of fossil fuels—is changing atmospheric chemistry (Pachauri and Reisinger 2007). These changes are expected to result in numerous climate-vegetation-disturbance changes with complex and incompletely understood interactions (Grulke 2008; Running 2008) including increased tree mortality (Allen and others 2010; McKenzie and others 2008), major shifts in fire regimes (Flannigan and others 2009; Krawchuk and others 2009a,b; Le Goff and others 2009; Liu and others 2010; Wotton and others 2010), and complex social reactions.

The activities of man are strongly tied to regional climatology. Throughout the development of civilization, the people inhabiting the land have responded to climate-vegetation shifts by changing land practices and migrating as productivity and disturbance patterns changed (Carto and others 2009; Dillehay 2009; Gupta and others 2006; Tipping and others 2008). Evidence suggests that human activities have strongly influenced vegetation (Anderson 2005; Betancourt and Van Devender 1981; Bond and others 2005; Moore 1972; Stewart 1956, 1982; Vale 2002) and likely climate (Ruddiman 2003, 2007), and populations and burning practices have ebbed and flowed (Carcaillet and others 2002, Nevle and Bird 2008; Ruddiman 2003, 2007; Ruddiman and Ellis 2009) over the millennia. Humans are dynamically coupled to their environment, climate, and vegetation. Fire is man's first tool. As we move forward, cultural resource specialists and fire managers will need to plan and adapt to meet the challenge to manage fire and protect cultural resources.

Conclusions

Vegetation/fuels, climate, and disturbance processes are dynamically coupled. Any change in one has feedbacks to the others. The vegetation/fuels on a site reflect the history of climate and terrain influences as well as past disturbances. The character of vegetation/fuels affects the potential occurrence and severity of future fires. Vegetation has developed throughout time with fire as a periodic disturbance agent, and fires will continue to occur, likely at an increased rate under a warming climate. The human family has developed through time closely coupled to the climate and vegetation. Humans have affected vegetation/fuels through use of fire as a land management tool. Fires have impacted cultures for millennia and fire will continue to impact contemporary cultures as well as the remnants of past cultures. The challenge is to manage vegetation/fuels to minimize damage to contemporary cultures as well as the cultural resources left by those who once lived on this land. Fires are highly variable both spatially and temporally, but the principles that govern fire are well known. Application of these principles can help to minimize the negative impacts of fuels treatment and restoration activities as well as inform post-fire inventory, monitoring, stabilization and rehabilitation plans. Critical to achieving this is the application of good local, site-specific knowledge about the combustion and fire environments juxtaposed to cultural resources. Currently, the application of fire principles to the wise management of cultural resources in fire prone environments is largely qualitative. We can bound the conditions where problems are more versus less likely to occur but we cannot predict them with accuracy because of the wide variation in field conditions. Research is needed to improve our ability to predict energy release and temperature histories associated with burning of various fuel beds. Improved fire science, when coupled with knowledge about the location and material characteristics of cultural resources, will lead to refined predictions and improved guidance for management of cultural resources.

Appendix 2-1—A Field Guide to Fire Severity Terminology and Classification

Fire Characteristics: Fire Intensity Classes

Fires burn throughout a continuum of energy release rates (table A-1) (Artsybashev 1983; Rothermel 1991; Rowe 1983; Van Wagner 1983). Ground fires burn in compact fermentation and humus layers and in organic muck and peat soils where they spread predominantly by smoldering (glowing) combustion and typically burn for hours to weeks. Forward rates of spread in ground fires range on the order of several inches (decimeters) to yards (meters) per day. Temperatures are commonly in excess of 300 °C (572 °F) for several hours (Agee 1993; Frandsen and Ryan 1986; Hartford and Frandsen 1992; Ryan and Frandsen 1991). The conditions necessary for ground fires are organic soil horizons greater than about 4 to 6 cm (1.6 to 2.4 in) deep and extended drying (Brown and others 1985; Miyanishi 2001; Reinhardt and others 1997). Surface fires spread by flaming combustion in loose litter, woody debris, herbaceous plants and shrubs, and trees roughly less than 2 m (6 ft) tall. Under marginal burning conditions, surface fires creep along the ground at rates of <1 m/hr with flames less than 0.5 m high (table A-1; fig. A-1.1). As fuel, weather, and terrain conditions become more favorable for burning, surface fires become progressively more active with spread rates ranging on the order of tens of meters (yards) to kilometers (miles) per day. The duration of surface fires is on the order of one to a few minutes (Frandsen and Ryan 1986; Hartford and Frandsen 1992; Vasander and Lindholm 1985) except where extended residual burning occurs beneath logs or in concentrations of heavy woody debris. Here flaming combustion may last a few hours resulting in substantial soil heating (Hartford and Frandsen 1992). However, the surface area occupied by long-burning woody fuels is typically small, less than 10 percent and often much less (Albini 1976; Albini and Reinhardt 1995; Dyrness and Youngberg 1957; Ryan and Noste 1985; Tarrant 1956). If canopy fuels are plentiful and sufficiently dry, surface fires begin to transition into crown fires (Scott and Reinhardt 2001; Van Wagner 1977). Crown fires burn in the foliage, twigs, and epiphytes of the forest or shrub canopy located above the surface fuels. Such fires exhibit the maximum energy release rate but are typically of short duration, 30 to 80 seconds. Fires burn in varying combinations of ground, surface, and crown fuels depending on the local conditions at the specific time a fire passes a given point. Ground fires burn independently from surface and crown fires and often occur some hours after passage of the flaming front (Artsybashev 1983; Hungerford and others 1995; Rowe 1983; Van Wagner 1983). Changes in surface and ground fire behavior occur in response to subtle changes in the microenvironment, stand structure, and weather, leading to a mosaic of fire treatments at multiple scales in the ground, surface and, canopy strata (Ryan 2002).

Table A-1—Representative ranges for fire behavior characteristics for ground, surface, and crown fires (from Ryan 2002).

Fire type	Dominant combustion phase	General description	Rate of spread (meters/minutes)	Flame length (meters)	Fireline intensity (kW/meter)
Ground	Smoldering	Creeping	3.3E-4 to 1.6E-2	0.0	<10
Surface	Flaming	Creeping	<3.0E-1	0.1-0.5	1.7E0-5.8E1
		Active/Spreading	3.0E-1 to 8.3E0	0.5-1.5	5.8E1-6.3E2
		Intense/ Running	8.3E0-5.0E1	1.5 to 3.0	6.3E2 to 2.8E3
Transition	Flaming	Passive crowning	Variable[a]	3.0 to 10.0	Variable[a]
Crowning	Flaming	Active crowning	1.5E1 to 1.0E2	5.0 to 15[b]	1.0E4 to 1.0E5
		Independent crowning	Up to ca. 2.0E2	Up to ca.70[b]	Up to ca. 2.7E6

[a] Rates of spread, flame length and fireline intensity vary widely in transitional fires. In subalpine and boreal fuels it is common for surface fires to creep slowly until they encounter conifer branches near the ground, then individual trees or clumps of trees torch sending embers ahead of the main fire. These embers start new fires, which creep until they encounter trees, which then torch. In contrast, as surface fires become more intense, torching commonly occurs prior to onset of active crowning. SI units to English units conversions: meters/minute x 3.28 = feet/minute, meters x 3.28 = feet, kW/meter x 0.2891 = BTU/ft.-s.

[b] Flame lengths are highly variable in crown fires. They commonly range from 0.5 to 2 times canopy height. Fire managers commonly report much higher flames but these are difficult to verify or model. Such extreme fires are unlikely to result in additional fire effects within a stand but are commonly associated with large patches of continuous severe burning.

A number of authors have broken the fire intensity continuum into classes typically for purposes of clear communication in the context of fire suppression activities (Alexander and Cole 1994; Alexander and de Groot 1989; Andrews and Rothermel 1982; Rothermel and Reinhardt 1983; Roussopoulos and Johnson 1975; Van Wagner 1982). For similar reasons it is useful to break the fire intensity continuum into classes for documenting and communicating the effects of fire on ecosystem components (Ryan 2002) and cultural resources. Table A-1 provides a descriptive classification of fire intensity. Figures A-1.1 to A-1.5 provide a visual reference for intensity classes. As with all classifications, it is important to recognize that there is some subjectivity when placing fires into a class, particularly near class boundaries. Also, it is important to recognize that there can be considerable variation in fire intensity across small spatial distances as elements in the fire environment change or multiple fire fronts converge. The appropriate use of a classification depends on the spatial and temporal scale of concern (fig. 2-1). The first-order effects on an artifact or feature depend on the intensity and depth of burn immediately adjacent to the artifact or feature. The first-order effects to a site depend more on the modal fire intensity and depth of burn in the general area. The second-order effects depend not only on the intensity and depth of burn at the site (i.e., first-order drivers) but also the modal condition of the surrounding landscape (e.g., erosion potential) (fig. 2-22).

Figure A-1.1—Fire intensity class 1: Creeping surface fires. Examples include: A. aspen, B. longleaf pine, C. ponderosa pine, D. black spruce (note: fires often creep in black spruce forests igniting and torching trees leading to localized higher intensity and spotting but the area is burned predominantly by creeping surface fires until the fire environment becomes dryer or windier).

Figure A-1.1 (Continued)

Figure A-1.2—Fire intensity class 2: Active/Spreading Surface Fires. Examples include: A. southern pine – oak, B. ponderosa pine, C. jack pine, and D. mixed conifer (Douglas-fir – ponderosa pine).

Figure A-1.2 (Continued)

C

D

A

Figure A-1.3—Fire intensity class 3: Intense/Running Surface Fires. Examples include: A. lodgepole pine, B. mountain big sagebrush, C. Southern pine – oak, and D. pocosin – pond pine woodland.

B

Figure A-1.3 (Continued)

Figure A-1.4—Fire intensity class 4: Passive Crowning/Torching. Examples include: A. black spruce, B. mixed conifer (lodgepole pine, ponderosa pine, Douglas-fir), C. individual lodgepole pine tree torching, and D. clump of ponderosa pine and Douglas-fir trees torching.

Figure A-1.4 (Continued)

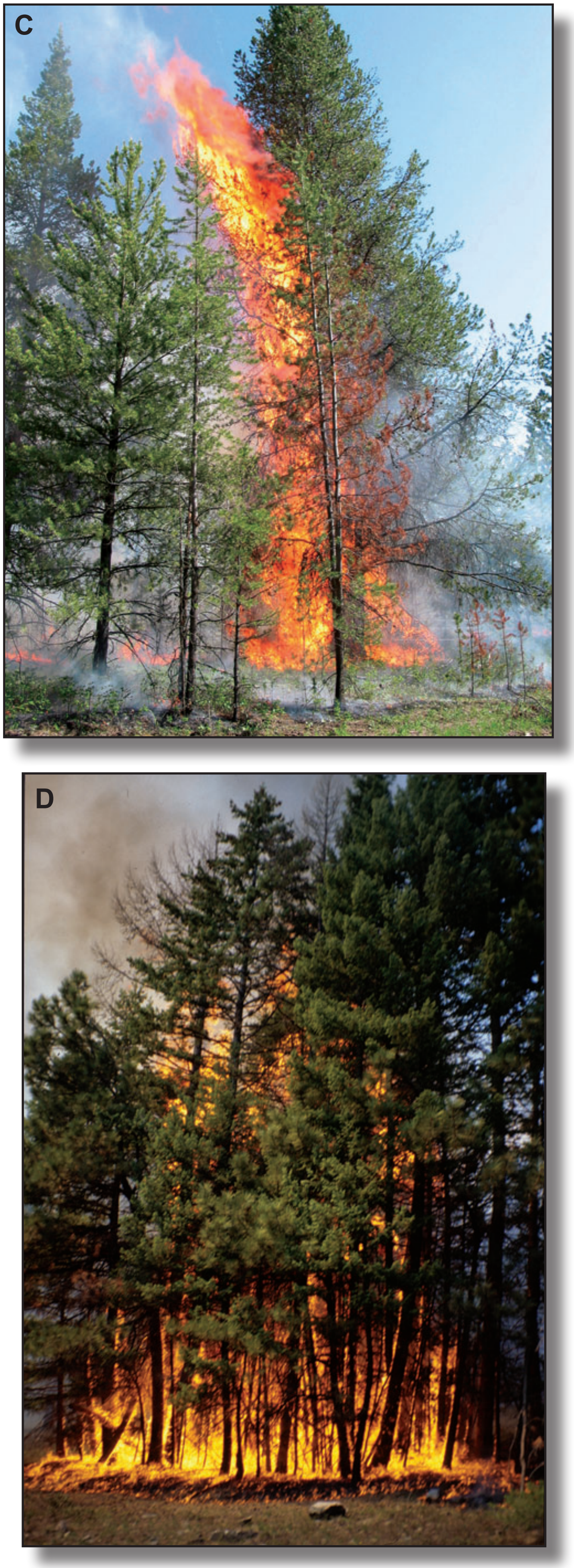

Figure A-1.5—Fire intensity class 5:Active Crowning. Examples include A. Douglas-fir, B. jack pine/black spruce, C. crown-fire in heavy chaparral, and D. black spruce – white spruce.

Figure A-1.5 (Continued)

C

D

Fire Characteristics: Depth of Burn Classes

Numerous authors have used measures of the depth of burn into the organic soil horizons or visual observation of the degree of charring and consumption of plant materials to define fire severity for interpreting the effects of fire on soils, plants, and early succession (Conrad and Poulton 1966; DeBano and others 1998; Dyrness and Norum 1983; Feller 1998; Johnson 1998; Miller 1977; Morgan and Neuenschwander 1988; Ohmann and Grigal 1981; Rowe 1983; Ryan and Noste 1985; Schimmel and Granström 1996;Viereck and Dyrness 1979; Viereck and Schandelmeier 1980; Zasada and others 1983). Depth of burn (DOB) is directly related to the duration of burning in woody fuels (Albini and Reinhardt 1995; Anderson 1969) and duff (Frandsen 1991a, b; Johnson and Miyanishi 2001). In heterogeneous fuels, depth of burn can vary substantially over short distances (e.g. beneath a shrub or tree canopy vs. the inter-canopy area, or beneath a log vs. not) (Ryan and Frandsen 1991; Tunstall and others 1976). At the spatial scale of a sample plot within a given fire, depth of burn can be classified on the basis of visual observation of the degree of fuel consumption and charring on residual plant and soil surfaces (Ryan 2002; Ryan and Noste 1985).

Ryan and Noste (1985) summarized literature on the relationships between depth of burn and the charring of plant materials. An adaptation of their table 2, updated to reflect subsequent literature (DeBano and others 1998; Feller 1998; Moreno and Oechel 1989; Pérez and Moreno 1998) and experience, particularly in peat and muck soils, is presented in table A-2. This table can be used as a field guide to classifying depth of burn on small plots (e.g., quadrats). The larger the plot area being described by a single class, the more the rating will approach the modal condition for the area and the less it will reflect finer scale variation, which may be important for understanding the fire treatment effects on a particular cultural feature. A brief description of depth of burn characteristics is provided for clarification of subsequent discussion of fire effects:

- *Unburned:* Plant parts are green and unaltered; there is no direct effect from heat. The extent of unburned patches (mosaics) varies considerably within and between burns as the fire environment (fuels, weather, and terrain) varies. Unburned patches are important rufugia for many species and are a source of plants and animals for recolonization of adjacent burned areas. Soil organic matter, structure, and infiltration rate are unchanged.
- *Scorched:* Fire did not burn the area, but radiated or convected heat from adjacent burned areas caused visible damage. Mosses and leaves are brown or yellow but species characteristics are still identifiable. Soil heating is negligible. Scorched areas occur to varying degrees along the edges of more severely burned areas. As it occurs on edges, the area within the scorched class is typically small (Dyrness and Norum 1983). Soil effects are typically similar to those in unburned areas. The scorched class may, however, have utility in studies of micro-variation of fire effects.
- *Light:* In forests, the surface litter, mosses, and herbaceous plants are charred-to-consumed but the underlying forest duff or organic soil is unaltered. Fine dead twigs up to 0.6 cm (0.2 in) are charred or consumed but larger branches remain. Logs may be blackened but are not deeply charred except where two logs cross. Leaves of understory shrubs and trees are charred or consumed but fine twigs and branches remain. In non-forest vegetation, plants are similarly charred or consumed; herbaceous plant bases are not deeply burned and are still identifiable. Charring of the mineral soil is negligible. Light DOB is associated with short duration fires either because of light fuel loads (i.e., low fuel mass per unit area), high winds, moist fuels, or a combination of these three factors. Typical forest-floor moisture contents associated with light DOB are litter (O_i) 15-25 percent and duff (O_e+O_a) greater than 125 percent. Impacts on infiltration and runoff are typically minimal. Reduction in leaf area may decrease interception and evapotranspiration but, as most soil-stored seeds, rhizomes, and other underground plant structures survive (Miller 2000; Ryan 2000), hydrologic recovery is typically rapid. Other names associated with this class include low depth of burn and low soil burn severity. Figure A-2.1 illustrates light depth of burn characteristics.
- *Moderate:* In forests, the surface litter, mosses, and herbaceous plants are consumed. Shallow duff layers are completely consumed and charring occurs in the top 1.2 cm (0.5 in) of the mineral soil. Where deep duff layers or organic soils occur, they are deeply burned to completely consumed resulting in deep char and ash deposits but the texture and structure of the underlying mineral soil are not visibly altered. In uplands, trees of late-successional, shallow-rooted species often topple or are left on root pedestals. Fine dead twigs are completely consumed, larger branches and rotten logs are mostly consumed, and logs are deeply charred. Burned-out stump holes and rodent middens are common. Leaves of understory shrubs and trees are completely consumed.

Table A-2—Visual characteristics of depth of burn in forests, shrublands, and grasslands from observations of ground surface characteristics, charring, and fuel consumption for unburned and light (Part A), moderate (Part B) and deep (Part C) classes (modified from Ryan and Noste 1985; Ryan 2002; Neary and others 2005).

	Vegetation type		
Depth of burn Class	**Forests**	**Shrublands**	**Grasslands**
Unburned			
Surface characteristics	Fire did not burn on the surface.		
Fuel characteristics	Some vegetation injury may occur from radiated or convected heat resulting in an increase in dead fuel mass.		
Occurrence:	A wide range exists in the percent unburned in natural fuels. Under marginal surface fire conditions, the area may be >50%. Under severe burning conditions, <5% is unburned. Commonly, 10-20% of the area in slash burns is unburned. Unburned patches provide refugia for flora and fauna.		
Light			
Surface characteristics	Leaf litter charred or consumed. Upper duff charred but full depth not altered. Gray ash soon becomes inconspicuous leaving a surface that appears lightly charred to black.	Leaf litter charred or consumed, but some leaf structure is discernable. Leaf mold beneath shrubs is scorched to lightly charred but not altered over its entire depth. Where leaf mold is lacking, charring is limited to <0.2 cm (0.1 in) into mineral soil. Some gray ash may be present but soon becomes inconspicuous leaving a blackened surface beneath shrubs.	Leaf litter is charred or consumed but some plant parts are discernable. Herbaceous stubble extends above the soil surface. Some plant parts may still be standing, bases not deeply burned, and still recognizable Surface is black after fire but this soon becomes inconspicuous. Charring is limited to <0.2 cm (0.1) into the soil.
Fuel characteristics	Herbaceous plants and foliage and fine twigs of woody shrubs and trees are charred to consumed but twigs and branches >0.6cm (0.2 in) remain. Coarser branches and woody debris are scorched to lightly charred but not consumed. Logs are scorched to blackened but not deeply charred. Rotten wood is scorched to partially burned.	Typically, some leaves and twigs remain on plants and <60% of brush canopy is consumed. Foliage is largely consumed whereas fine twigs and branches >0.5 cm (0.2 in) remain.	Typically, 50 to 90% of herbaceous fuels are consumed and much of the remaining fuel is charred.
Occurrence	Light DOB commonly occurs on 10-100 percent of the burned area in natural fuels and 45-75% in slash fuels. Low values are associated with marginal availability of fine fuels whereas high values are associated with continuous fine fuels or wind-driven fires.	In shrublands where fine fuels are continuous, light DOB occurs on 10-100% depending on fine fuel moisture and wind. Where fine fuels are limited, burns are irregular and spotty at low wind speeds. Moderate to high winds are required for continuous burns.	Burns are spotty to uniform, depending on grass continuity. Light DOB occurs in grasslands when soil moisture is high, fuels are sparse, or fires burn under high wind. This is the dominant type of burning in most upland grasslands.
Moderate			
Surface characteristics	In upland forests, litter is consumed and duff deeply charred or consumed, mineral soil not visibly altered but soil organic matter has been partially pyrolyzed (charred) to a depth >1.0cm (0.4 in). Grey or white ash persists until leached by rain or redistributed by rain or wind. In forests growing on organic soils, moderate DOB fires partially burn the root-mat but not the underlying peat or muck.	In upland shrublands, litter is consumed. Where present, leaf mold deeply charred or consumed. Charring 1 cm (0.4 in) into mineral soil, otherwise soil not altered. Gray or white ash quickly disappears. In shrub-scrub wetlands growing on organic soils, moderate DOB fires partially burn the root-mat but not the underlying peat or muck.	In upland grasslands, litter is consumed. Charring extends to <0.5 cm (0.2 in) into mineral soil, otherwise soil not altered. Gray or white ash quickly disappears. In grasslands, sedge meadows and prairies growing on organic soils moderate DOB fires partially burn the root-mat but not the underlying peat or muck.

Table A-2—Continued

	Vegetation type		
Depth of burn Class	**Forests**	**Shrublands**	**Grasslands**
Fuel characteristics	Herbaceous plants, low woody shrubs, foliage and woody debris <2.5 cm (1 in) diameter consumed. Branch-wood 2.5 to 7.5 cm (1-3 in) 90+ percent consumed. Skeletons of larger shrubs persist. Logs are deeply charred. Shallow-rooted, late successional trees and woody shrubs typically topple or are left on pedestals . Burned-out stump holes are common.	Herbaceous plants are consumed to the ground-line. Foliage and branches of shrubs are mostly consumed. Stems <1 cm (0.4 in) diameter are mostly consumed. Stems >1 cm (0.4 in) mostly remain.	Herbaceous plants are consumed to the ground-line.
Occurrence	Moderate DOB occurs on 0-100% of natural burned areas and typically 10-75% on slash burns. High variability is due to variability in distributions of duff depth and woody debris.	Moderate DOB varies with shrub cover, age, and dryness. It typically occurs beneath larger shrubs and increases with shrub cover. Typically, burns are more uniform than in light DOB fires.	Moderate DOB tends to occur when soil moisture is low and fuels are continuous. Then burns tend to be uniform. In discontinuous fuels high winds are required for high coverage in moderate DOB.
Deep			
Surface characteristics	In forests growing on mineral soil, the litter and duff are completely consumed. The top layer of mineral soil visibly altered. Surface mineral soil structure and texture are altered and soil is oxidized (reddish to yellow depending on parent material). Below oxidized zone, >1 cm (0.4 cm) 2of mineral soil appears black due to charred or deposited organic material. Fusion of soil may occur under heavy woody fuel concentrations. In forests growing on organic soils, deep DOB fires burn the root-mat and the underlying peat or muck to depths that vary with the water table.	In shrublands growing on mineral soil, the litter is completely consumed leaving a fluffy white ash surface that soon disappears. Organic matter is consumed to depths of 2-3 cm (0.8-1.2 in). Colloidal structure of surface mineral soil is altered. In shrub-scrub wetlands growing on organic soils deep DOB fires burn the root-mat and the underlying peat or muck to depths that vary with the water table.	In grasslands growing on mineral soil, the litter is completely consumed leaving a fluffy white ash surface that soon disappears. Charring to depth of 1 cm (0.4 in) in mineral soil. Soil structure is slightly altered. In grasslands growing on organic soils, deep DOB fires burn the root-mat and the underlying peat or muck to depths that vary with the water table.
Fuel characteristics	In uplands, twigs and small branches are completely consumed. Few large, deeply charred branches remain. Sound logs are deeply charred and rotten logs are completely consumed. In wetlands twigs, branches, and stems not burned in the surface fire may remain even after subsequent passage of a ground fire.	In uplands, twigs and small branches are completely consumed. Large branches and stems are mostly consumed. In wetlands twigs, branches, and stems not burned in the surface fire may remain even after subsequent passage of a ground fire.	All above ground fuel is consumed to charcoal and ash.

Figure A-2.1—Light depth of burn. A. sagebrush-grass (mixture of light depth-of-burn (DOB) beneath sagebrush and unburned grass), Beaverhead-Deerlodge National Forest, Montana; B. ninebark mountain shrub community (mixture of light with some moderate under denser shrubs), Lolo National Forest, Montana; C. pocosin – pond pine woodland, Dare County Bombing Range, North Carolina; D. feather moss, Tetlan National Wildlife Refuge, Alaska (transitions to moderate DOB on left); E. glacier lilies growing from just beneath lightly charred lodgepole pine duff, Yellowstone National Park, Wyoming (lethal heat penetration into soil <5 mm (0.2 in.) as evidenced by tissue regrowth); F. sagebrush – grass, Bridger-Teton National Forest, Wyoming; G. ponderosa pine (note litter charred but underlying fermentation uncharred; H. following crown fire in jack pine-black spruce in Northwest Territories, Canada (note logs not charred on bottom, surface needles blackened but not consumed); I. light logging slash, Mt. Hood National Forest, Oregon (note logs and surface litter blackened but not deeply charred, much fine woody debris was unconsumed).

Figure A-2.1 (Continued)

C

D

Figure A-2.1 (Continued)

E

F

Figure A-2.1 (Continued)

G

H

Figure A-2.1 (Continued)

I

Fine twigs and branches of shrubs are mostly consumed (this effect decreases with height above the ground), and only the larger stems remain. Shrub stems frequently burn off at the base during the ground fire phase leaving residual aerial stems that were not consumed in the flaming phase lying on the ground. In non-forest vegetation, plants are similarly consumed, herbaceous plant bases are deeply burned and unidentifiable. In shrublands, average char-depth of the mineral soil is on the order of less than 1 cm (0.4 in) but soil texture and structure are not noticeably altered. Charring may extend 2 to 3 cm (0.8 to 1.2 in) beneath shrubs where deep litter and duff were consumed. Typical forest-floor moisture contents associated with moderate DOB are litter (O_i) 10 to 20 percent and duff (O_e+O_a) less than 75 percent. The depth at which plant tissues are killed and hydrophobic layers are formed increases with the depth of the organic horizon, or log diameter, consumed. Ash depth also increases with depth of duff consumed. Figure A-2.2 illustrates moderate depth of burn characteristics.

- *Deep:* In forests growing on mineral soil, the surface litter, mosses, herbaceous plants, shrubs, and woody branches are completely consumed. Sound logs are consumed or deeply charred. Rotten logs and stumps are consumed. The top layer of the mineral soil is visibly oxidized, reddish to yellow. Surface soil texture is altered and, in extreme cases, fusion of particles occurs. A black band of charred organic matter 1 to 2 cm (0.4 to 0.8 in) thick occurs at variable depths below the surface. The depth of this band increases with the duration of extreme heating. The temperatures associated with oxidized mineral soil are typical of those associated with flaming >500 °C (>932 °F) rather than smoldering <500 °C (<932 °F). Thus, deep depth of burn typically only occurs where woody fuels burn for extended duration such as beneath individual logs or concentrations of woody debris, and in harvester ant mounds and litter-filled burned-out stump holes. Moisture content of logs >3 in (7.6 cm) diameter is typically <10 percent. Representative forest-floor moisture contents associated with deep depth of burn are litter (O_i) less than 15 percent and duff (O_e+O_a) less than 30 percent. In areas with deep organic soils, deep depth-of-burn occurs when ground fires consume the root-mat or burn beneath the root-mat. Trees often topple in the direction from which the smoldering fire front approached (Artsybashev 1983; Hungerford and others 1995; Wein 1983). Other names associated with this class include high depth of burn, severe burn, and high soil burn severity. We prefer the term "deep" as it better reflects the physical process of heat penetration into the soil. Figure A-2.3 illustrates deep depth of burn classes.

The moderate depth of burn class is a broad class. Some investigators have chosen to divide the class into two classes (c.f. Feller 1998). In practice we have found it difficult to do so on the basis of post-hoc examination of the mineral soil alone, but rely on the preponderance of the evidence, which includes reconstructing the prefire vegetative structure. The depth-of-burn characteristics are appropriate for quadrat-level descriptions. At higher spatial scales, logic needs to be developed for defining fire severity on the basis of the distribution of depth of burn classes (c.f. DeBano and others 1998; Ryan and Noste 1985).

Fire Severity Matrix

Ryan and Noste (1985) combined fire intensity classes with depth of burn (char) classes to develop a two-dimensional matrix approach to defining fire severity. The basis for these characteristics is that fire-intensity classes qualify the relative energy release rate for a fire, whereas depth-of-burn classes qualify the relative duration of burning. Their concept focuses on the ecological work performed by fire both above ground and below ground. The matrix provides an approach to classifying the level of fire treatment or severity for ecological studies at the scale of the individual and the community. The approach has been used to interpret differences in plant survival and regeneration (Smith and Fischer 1997; Willard and others 1995) and to field-validate satellite-based maps of burned areas (White and others 1996). The matrix has been used to develop a conceptual model of post-fire regeneration potential (Ryan 2002) and potential impacts on soils and watersheds (Neary and others 2005). The Ryan and Noste (1985) conceptual model of fire severity can also be used and as a means of documenting the level of fire treatment in prescribed fires and wildfires for the purposes of evaluating the effects of fire on cultural resources (table A-3). Other investigators have developed similar classifications (c.f., DeBano and others 1998; Jane and others 2009) with somewhat different class definitions. However, they all employ similar logic in that the rate of organic matter consumption (represented by rate of energy release in fire intensity classes) and the magnitude of organic matter consumption (represented in depth of burn classes) affect numerous ecosystem states and processes.

A

Figure A-2.2—Moderate depth of burn. A. complete duff consumption aspen-mixed conifer Bridger-Teton National Forest, Wyoming; B. complete duff consumption aspen, Caribou National Forest, Idaho; C. complete duff consumption beneath white ash, light DOB in blackened areas, Douglas-fir, Lubrecht Experimental Forest, Montana; D. Sagebrush – grass Yellowstone National Park, Wyoming (moderate DOB mid ground, elsewhere lite DOB and unburned); E-F. following a crown-fire in jack pine – black spruce Northwest Territories, Canada (note litter consumed to white ash but underlying fermentation and humus not altered (light DOB) except where residual burning of crossed logs (E) resulted in moderate DOB (F) where duff and logs were completely consumed at their intersection; G. moderate depth of burn on an extremely fragile high elevation site (obsidian-derived soil, no vascular plants survived or colonized 1 year after 1988 North Fork Fire, a crown-fire/moderate depth-of-burn fire, Moose Creek Research Natural Area, Targee, National Forest, Idaho); H. Douglas-fir duff mostly consumed but underlying mineral soil not visibly altered and logs charred, Willamette National Forest, Oregon.

Figure A-2.2 (Continued)

Figure A-2.2 (Continued)

D

E

Figure A-2.2 (Continued)

Figure A-2.2 (Continued)

H

A

Figure A-2.3—Deep depth of burn class. A. charred, black layer beneath oxidized soil and ash; B. charred, black layer beneath oxidized soil and ash plus deeply charred log; C. charred, black layer beneath oxidized soil; D. 20 cm (8 in.) duff pin (nail) documented duff consumption next to a partially rotten log that burned out. Deep ash deposits are occasionally mistaken for oxidized mineral soil. Ash is fine and powdery when dry and slick and greasy when wet whereas oxidized soil retains pebbles and granularity. The black zone corresponds roughly with the depth at which 250 °C (482 °F) was maintained in the soil profile. E. deeply burned soil and western larch stem resulting from burnout of heavy concentration of coarse woody debris, Lolo, National Forest, Montana; F. reburned forest (note: second fire consumed logs created by first fire leading to deep DOB (light color) whereas intervening areas had little residual fuel and less soil heating (dark color); G. ponderosa pine stump-hole and log burn-out (note: localized deep DOB where stump and log burned out, otherwise light DOB and unburned except moderate DOB where duff mounds burned-out beneath old pine (not shown).

Figure A-2.3 (Continued)

B

C

Figure A-2.3 (Continued)

D

E

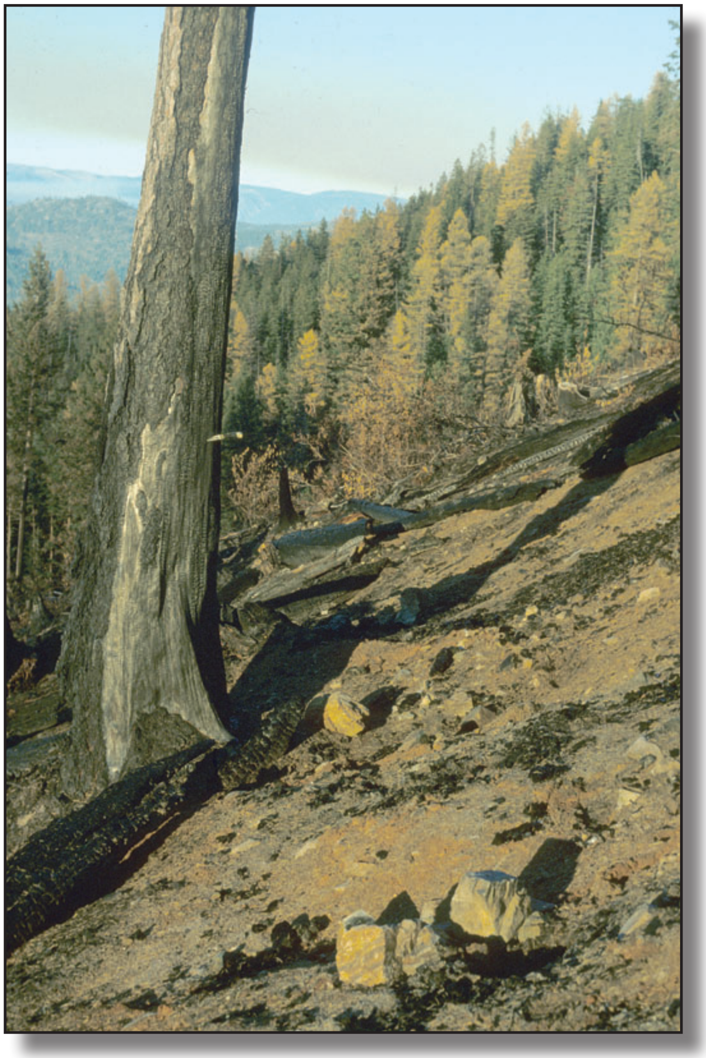

Figure A-2.3 (Continued)

F

G

Table A-3—Fire severity matrix for evaluating and documenting the effects of fire on cultural resources. Fire intensity classes relate to the heat pulse up and the potential to damage above ground cultural resources (artifacts) and those exposed on the pre-fire surface of the ground. Depth of burn classes relate to the heat pulse down and the potential to damage cultural resources in the soil.[a]

Fire severity matrix for cultural resources				
	Depth of burn class			
Fire intensity class	**Unburned**	**Light**	**Moderate**	**Deep**
Crowning	Limited to transition zone between burned and unburned. Above ground resources may be damaged by radiant heat or combustion deposits (tar, soot, etc.).	Common occurrence in early-season fires when humus is wet (>120%), in undisturbed wetlands with high water table, and in areas with exposed mineral soil. Above-ground and surface CR exposed to high temperatures for short duration and combustion deposits. Damage restricted to exposed CR and top 1 cm (0.4 in) in soil.	Common occurrence in forests with moderate duff depths (5 to 10 cm [2-3.9 in]) and duff moisture <50%. Above-ground CR exposed to high temperatures for short duration and combustion deposits. Severe damage is common to all exposed CR and artifacts in top 5 cm (2 in) of the ground.	Common in forests with deep duff (>10cm [3.9 in]) or heavy CWD. High energy release rate and long residence time associated with deep depth of burn leads to maximum potential damage to both above and below ground CR. Available fuel approximately equals total fuel. Damage may extend to artifacts in top 10 cm (3.9 in) of mineral soil. Loss of canopy interception, deep soil heating, and heavy ash increase potential for post-fire erosion.
Torching	See above	See above. The primary distinction is in the spatial scale uniformity of heating to exposed CR.	See above. The primary distinction is in the spatial scale uniformity of heating to exposed CR.	See above. The primary distinction is in the spatial scale uniformity of heating to exposed CR.
Intense running surface fire	See above. Damaging distance from burned edge is less due to lower intensity.	Common in fire environments where heavy surface fuel loadings burn under low humidity and moderate to strong winds and when duff is shallow (<5 cm [2 in]) or moist (>120%) and where over-story stratum is sparse or vertical fuel continuity is poor due to high crown base height. Effect of CR similar to above except that height of thermal damage restricted to < 5 meters (16 feet) above ground. Damage restricted to exposed CR and top 1 cm in soil.	Common in fire environments where heavy surface fuel loadings burn under low humidity and moderate to strong winds and where duff is moderately deep (5 to 10 cm [2-3.9 in]) and dry (duff moisture <50 %). Often occurs in head-fires and on the flanks of crown fires. Damage common to exposed CR <5 m (16 ft) above the ground and artifacts in top 5 cm of mineral soil.	Common in fire environments where heavy surface fuel loadings burn under low humidity and moderate to strong winds and where duff is deep (>10 cm [3.9 in]) and dry (duff moisture <80 %, once ignited peat soil and deep organic soils may burn up to 120% moisture content), and beneath rotten logs. Often occurs in head-fires and on the flanks of crown fires. Damage common to exposed CR <5 m (16 ft) above the ground and artifacts in top 10 cm (3.9 in) of mineral soil.

Table A-3—Continued

Fire severity matrix for cultural resources				
	Depth of burn class			
Fire intensity class	**Unburned**	**Light**	**Moderate**	**Deep**
Actively spreading surface fire	Edge effect intermediate between above and below	Common in numerous fire environments where surface fuels support active burning. Effects on CR intermediate to above and below. Less thermal effects than above, residue deposits possible to exposed CR at the surface or <4 meters (13 feet). Thermal damage restricted to exposed CR near the surface (<2 meters [6.5 feet] above ground) and top 1 cm (0.4 in) in soil.	Common in numerous fire environments where surface fuels support active burning. Effects on CR intermediate to above and below. Less thermal effects than above, residue deposits possible to exposed CR at the surface or <4 meters (13 feet). Thermal damage restricted to exposed CR near the surface (<2 meters [6 feet] above ground) and top 5 cm (2 in) in soil.	Common in numerous fire environments where surface fuels support active burning and duff is deep (5-to-10 cm deep (>10 cm [3.9 in]) and moderately dry (<80% once ignited peat soil and deep organic soils may burn up to 120% moisture content), and beneath rotten logs. Thermal damage common to exposed CR near the surface (<2meters [6 feet] above ground) and artifacts in top 10 cm (3.9 in) of mineral soil.
Creeping surface fire	Edge effect on exposed surface artifacts limited to a few millimeters.	Common under marginal burning conditions due to sparse fine fuels or high humidity, and in backing fires. Thermal damage restricted to exposed CR near the surface and top 1 cm in soil.	Common under marginal burning conditions due to sparse fine fuels or high humidity, and in backing fires where duff is intermediate (5-to 10 cm deep [2-3.9 in]) and dry (<50%). Thermal damage common to exposed CR near the surface and artifacts in top 5 cm (2 in) of soil.	Common under marginal burning conditions due to sparse fine fuels or high humidity, and in backing fires where duff is >10 cm (3.9 in) deep and moderately dry (<80%), and beneath rotten logs. Thermal damage common to exposed CR near the surface and artifacts in top 10 cm of mineral soil.
Unburned	No direct effect of fire on CR at the fine scale. Isolates unaffected. The burn mosaic may alter the visual character and experience of the cultural landscape	NA	NA	NA

[a] Typically, the burn- no-burn boundary is mineral soil surface in upland forests, woodlands, shrublands, and grasslands. In wetlands and temperate old-growth forests with deep organic soils, fires may burn vertically until they reach a moisture limit around 100% on an oven dry basis.