CHAPTER 3

Fire as a Physical Process

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> Where there's smoke, there's fire.
>
> ANONYMOUS

In many California ecosystems, the process of decomposition is too slow to completely oxidize accumulated organic material, and another process, such as fire, steps in to perform that role. The mediterranean climate in California, with its hot, dry summers and cool, wet winters, is not conducive to decomposition. When it is warm enough for decomposer organisms to be active, it's too dry. Conversely, when it's wet enough, it's too cold. As a result, decomposition is unable to keep up with the deposited material, and organic debris begins to accumulate. This debris becomes fuel available for the inevitable fire that will occur. All that is needed is a sufficient amount of fuel, an ignition source, and weather conditions conducive to burning. In this chapter we will look at fire as a physical process including combustion, fuel characteristics, fuel models, fire weather, ignition sources, mechanisms for fire spread, and fire effects.

Combustion

Combustion is one of many types of oxidation processes. These processes combine materials that contain hydrocarbons with oxygen and produce carbon dioxide, water, and energy. Oxidation is the reverse of photosynthesis, where energy is used in combination with carbon dioxide and water to produce organic material. The rate of oxidation can vary from the slow hardening of a coat of linseed oil in a paint film to the instantaneous explosion of a petrochemical. Combustion is a chain reaction that occurs rapidly at high temperatures.

Combustion Chemistry

Byram (1959) presents the chemical equation for combustion using a formula for wood that approximates its carbon, hydrogen, and oxygen contents. Although moisture content affects the amount of fuel available for combustion, water does not take part in the combustion reaction. Nitrogen, which is also a constituent of organic material, has little effect on combustion. If moisture and nitrogen are not included, the combustion equation is:

$$4C_6H_9O_4 + 25O_2 \rightarrow 18H_2O + 24CO_2 + 5{,}264{,}729 \text{ kJ}.$$

The energy produced by this reaction is called the *heat* of combustion. The 5,264,729 kJ (4,990,000 Btu) for the 4 moles of fuel is equivalent to 20 MJ kg^{-1} (8,600 Btu lb^{-1}) of fuel. See sidebar 3.1 for further discussion on different units and their derivation. The heat is produced from the fuel once it is ignited. For combustion to occur, fuel, oxygen, and heat must be present. These three factors form the *fire triangle* and fire control measures are based on breaking the link among them (Fig. 3.1). For example, a fire can be extinguished by removing the fuel, reducing the amount of oxygen, or by lowering the temperature of the fuel. In most wildland fires, combustion is incomplete and not all fuel is consumed.

The amount of heat produced by a fire is less than would occur under conditions of complete combustion. Some heat is lost through radiation, but the primary loss comes from the vaporization of moisture. Four separate steps are involved in this process: (1) heat is required to raise the temperature of the water in the fuel to boiling, (2) bound water must be released from the fuel, (3) the water must be vaporized, and (4) the water vapor must be heated to flame temperature. Only the heat necessary to release the bound water and to vaporize the water can be considered true losses (Byram 1959). The result of subtracting these two values from the heat content is called the *low heat content* or *heat yield*. If there is too much moisture in the fuel, combustion is unable to occur. The threshold level of moisture is called the *moisture of extinction*.

SIDEBAR 3.1. ENERGY UNITS, THEIR DERIVATION, AND THEIR RELATIONSHIPS

We are all familiar with calories—the nutritional content of food and the curse of all dieters. There are several other energy units that are less familiar but equally important. *British thermal units* (Btu) are used to measure the output of furnaces and air conditioners, and *kilowatt hours* (kW h) keep track of our electricity use. There are many types of energy, but all energy can be measured using the same unit, the *joule* (J). It was named after the British physicists James Prescott Joule and is the amount work done to produce the power of one watt (w) for one second (s), such as lifting 102 g (e.g., a small apple) through one meter under the earth's gravity. The joule is the preferred metric unit for energy, and the *megajoule* (MJ) is the unit used by fire scientists to measure the amount of heat energy in fuels.

The nutritional calorie is actually 1,000 calories (cal) and is called a *kilocalorie* (kcal). A calorie (cal) is the amount of heat necessary to raise the temperature of one gram of water one degree Celsius from 15°C–16°C and is equal to 4.184 J. Similarly, the Btu is the amount of heat necessary to raise one pound of water one degree Fahrenheit from 60°F to 61°F. It is equivalent to 1,054 J.

The kilowatt hour (kW h) corresponds to one kilowatt (kW) of power being used over a period of one hour and is equal to 3.6×10^6 J. Although the kW h is not used to describe fire behavior, the kilowatt (kW) is part of one measure of fire intensity. Fireline intensity, which is described as the amount of energy received per second along one meter of the fire front, is measured in units of kW m^{-1}.

Regardless of what units are used, the basic concept remains the same. Energy is stored in fuel and is released during combustion. The rate of that release is governed by many factors discussed in the remainder of this chapter.

FIGURE 3.1. The fire triangle illustrates the requirements for combustion; heat must be applied to fuel in the presence of oxygen for combustion to occur.

Heat Transfer

The heat resulting from combustion is transferred by three primary mechanisms: conduction, convection, and radiation. *Conduction* occurs when heat moves from molecule to molecule and is the only mechanism that can transfer heat through an opaque solid. Conduction is the reason you are likely to drop a frying pan that has been on the fire when you grab it by its handle. Heat moves by conduction through branches and into the center of logs. Fuel temperature is thus increased and water is driven out of the solid fuels. Conduction also occurs when flames come into direct contact with unburned fuels.

Convection is the movement of heat in a gas or a liquid. You can feel heat moving by convection when you put your hand above a campfire. As heat rises from a flaming front, convection transfers heat to the canopy of trees and preheats fuels in front of the flames. This can lead to torching of individual trees and to crown fires. Heat transfer by convection is enhanced by wind and steep slopes and is instrumental in

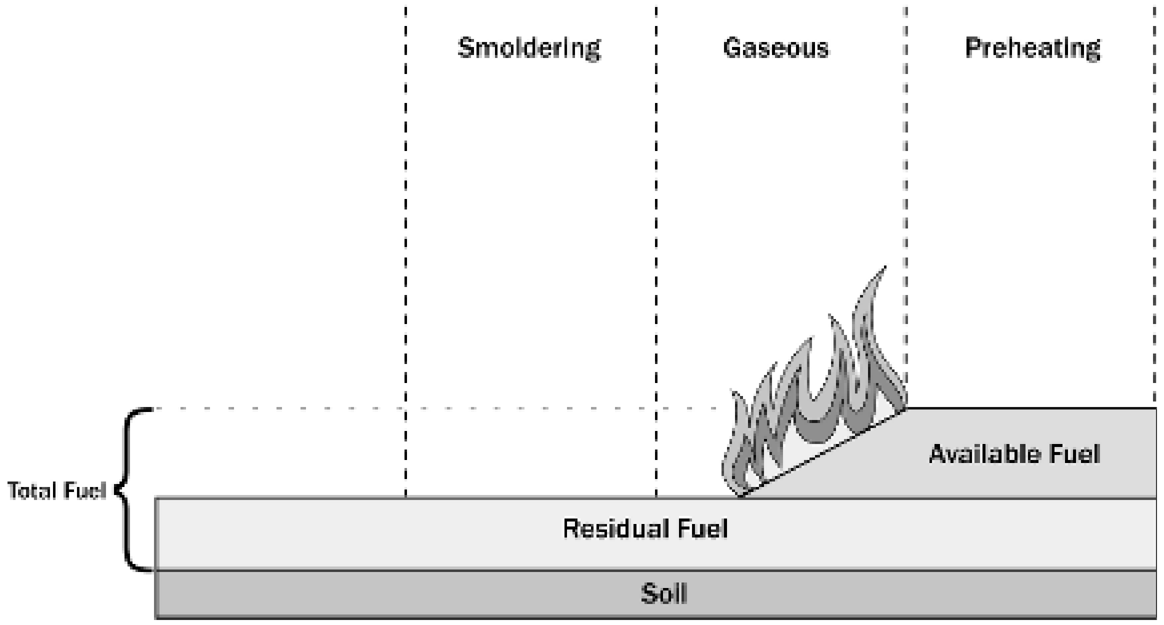


FIGURE 3.2. The three phases of combustion. Available fuel is the amount of fuel actually consumed. Combustion continues during the smoldering phase after passing of the flaming front.

lofting firebrands that produce new fires, called *spot fires,* ahead of the flaming front.

Heat transfer by *radiation* occurs in a straight line through transparent solids, liquids, and gases. Radiation preheats fuels and can cause spontaneous ignitions. This heat is felt while standing in front of a fire and is inversely proportional to the square of the distance away from the source. If you move half the distance toward a campfire, you will receive four times as much heat through radiation. This is why flames that are bent over by wind or are closer to adjacent fuels due to the slope are more effective in preheating and drying those fuels.

Combustion Phases

In wildland fuels, combustion occurs in three phases: preheating, gaseous, and smoldering (Fig. 3.2). During the *preheating* phase, fuels ahead of the fire are heated, water is driven out of the fuel, and gases are partially distilled (Byram 1959). The *gaseous* phase starts with ignition as gases continue to be distilled and active burning begins. During this phase oxidation is initiated and an active flaming front develops. The flames come from the burning distilled gases; both water and carbon dioxide are given off as invisible combustion products. Incomplete combustion results in condensation of some of the gases, and water vapor as small droplets of liquid or solid are suspended over the fire and produce smoke. During the *smoldering* phase, charcoal and other unburned material remaining after the flaming phase continue to burn leaving a small amount of residual ash (Byram 1959). During this phase the fuel burns as a solid and oxidation occurs on the surface of the charcoal. One of the products of incomplete combustion during the soldering phase is carbon monoxide.

Fuel

Fuel is the source of heat that sustains the combustion process. Fuels are characterized by physical and chemical properties that affect combustion and fire behavior.

Fuel Characteristics

Under constant weather and topographic conditions, the characteristics of the fuels determine the rate of combustion. For example, a fire burning in dry-grass fuels on a 20% slope with an 8 km h^{-1} (5 mi h^{-1}) wind would have a higher rate of spread and be more intense than would a fire burning an equivalent weight of woody debris under identical conditions. Similarly, a tall brush field would burn more intensely than would an equivalent amount of fuel arranged into a fuel complex with larger particles and less depth. Fine, porous fuels heat more quickly and burn more readily than coarse, compact fuels. The moisture contained in grass, wood, or shrub fuels also affects combustion—the drier the fuel, the more rapid the combustion.

SURFACE AREA TO VOLUME RATIO

Fuel coarseness, or fineness, is a function of fuel particle size. Imagine trying to start a log on fire in your wood stove with a single match. The log would not ignite because you would not be able to raise its temperature to ignition temperature. Instead you would split the log into many individual pieces of kindling. Although the volume of wood has not changed, the surface area of all the kindling is much greater than the surface area of the log (Box 3.1). The smaller the size of a fuel

BOX 3.1. THE SURFACE AREA TO VOLUME RATIO

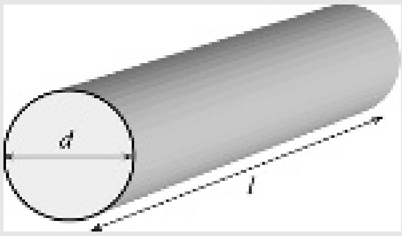
This ratio is calculated by dividing the surface area of a fuel particle by its volume:

$$SV = \frac{\pi d l}{\pi (d/2)^2 l}.$$

If you ignore the ends, the equation is simplified to dividing 4 by the diameter of the particle:

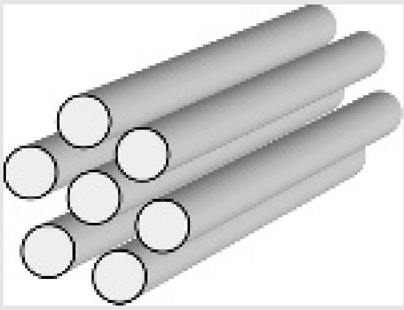
$$SV = \frac{4}{d}.$$

The ratio is increased if you split the fuels into smaller parts. For example, take a log with a diameter of 6:



if $d = 6$,
$SV = 0.67$.

When split into 7 pieces, the ratio increases from 0.67 to 14:



if $d = 2$,
$SV = 2$
and
$7 \times 2 = 14$.

particle, the larger the ratio between its surface and the volume. The surface area to volume ratio is measured in units of $m^2\ m^{-3}$ ($ft^2\ ft^{-3}$) or, for simplicity, m^{-1} (ft^{-1}). For long, cylindrical fuel particles such as conifer needles, twigs, branches, and grasses, the area of the ends can be ignored, and the ratio is determined by dividing the diameter into the number 4 (Burgan and Rothermel 1984). Leaves from broad-leaved plants also have high surface area to volume ratios that can be approximated by dividing the leaf thickness into the number 2. For example, an oak leaf with a thickness of 0.0005 m (0.0016 ft) would have a surface area to volume ratio of 4,000 m^{-1} (1,220 ft^{-1}). This ratio is an extremely important fuel characteristic because as more surface area is available for combustion, heating of the entire particle is quicker, and moisture is driven off more easily.

FUEL MOISTURE TIMELAG CLASS

The proportion of a fuel particle that contains moisture is a primary determinant of fire behavior. The interaction of a fuel particle with the ambient moisture regime is dependent on its size or its depth in the organic layer called duff. The size classes that are traditionally used to categorize fuels correspond to fuel moisture timelag classes (Deeming et al. 1977). *Timelag* is the amount of time necessary for a fuel component to reach 63% of its equilibrium moisture content at a given temperature and relative humidity (Lancaster 1970). Table 3.1 shows the various timelag classes and the corresponding woody size classes and duff depth classes.

One-hour timelag fuels consist of dead herbaceous plants and small branchwood as well as the uppermost litter on the forest floor. These fuels react to hourly changes in relative humidity. Day-to-day changes in moisture are reflected in the 10-hour fuels. The 100-hour fuels capture moisture trends spanning from several days to weeks, whereas 1,000-hour fuels reflect seasonal changes in moisture. The firewood analogy applies here as well. Your large logs would take several months to dry if left out in the rain for the winter, yet kindling, if brought inside, would dry in a few hours.

PACKING RATIO

Fuelbed compactness is another fuel characteristic that affects fire behavior. Again, imagine compressing all the kindling you just split into a tight bundle and trying to light the bundle; the kindling would probably not ignite. Remembering all the campfires you have lit, you would instead arrange the kindling into a small log cabin or teepee. The volume of wood has not changed, but the amount of air in the fuel bed has increased (Box 3.2). Fuelbed compactness, called the *packing ratio,* is measured by dividing the bulk density of the fuelbed, including fuel and air, by the fuel particle density (Burgan and Rothermel 1984). A solid block of wood has a packing ratio of one. If the packing ratio is too high, not enough oxygen can reach the fuel and combustion cannot occur. Conversely, if the packing ratio is too low, the fire has trouble spreading from particle to particle as the distance between particles increases and radiation decreases. The compactness at which maximum energy release occurs is called the *optimum* packing ratio. The closer the *actual* packing ratio is to the *optimum*, the more intense the fire will be. This concept is similar to adjusting the carburetor or fuel injectors on your car to reach the optimum mixture of fuel and air. If the mixture is too rich or too lean, the engine will not burn fuel efficiently.

FUEL LOAD

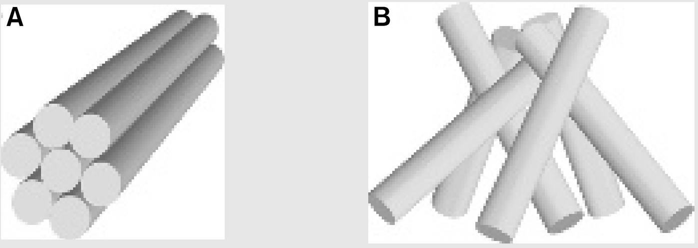
The amount of fuel that is potentially available for combustion has a differential effect on fire spread and intensity. As a heat source, the more fuel available, the greater the amount

TABLE 3.1

Moisture timelag classes and corresponding woody fuel size and duff fuel depth classes

Timelag Class	*Time Period*	*Woody Fuel Size Class* (cm.)	*Woody Fuel Size Class* (in.)	*Duff Fuel Depth Class* (cm.)	*Duff Fuel Depth Class* (in.)
1-hour	Hourly	0.00–0.64	0.00–0.25	0.00–0.64	0.00–0.25
10-hour	Daily	0.25–2.54	0.25–1.00	0.64–1.91	0.25–0.75
100-hour	Weekly	2.54–7.62	1.00–3.00	1.91–l0.16	0.75–4.00
1,000-hour	Seasonally	7.62–22.86	3.00–9.00	10.16+	4.00+

BOX 3.2. THE PACKING RATIO



The packing ratio is the proportion of fuel in a unit volume of fuelbed. The same amount of fuel can be packed (A) tightly with only 10% air or (B) loosely with 90% air.

of energy released. Rate of spread may actually decrease as fuel load increases, however, because the extra fuel also becomes a greater heat sink, and more heat is required to raise it to ignition temperature. Much of the response depends on the size class of the fuel, its packing ratio, and whether or not it is dead or live fuel. Procedures for inventorying downed woody fuels are found in Brown (1974) and Brown et al. (1982).

HEAT CONTENT

The low heat content of the fuel provides the energy to drive combustion. Rate of spread varies directly with heat content; doubling the heat content results in a two-fold increase in rate of spread. Heat content is measured in MJ kg^{-1} (Btu lb^{-1}).

Fuel Models

Fuel types that have similar characteristics are grouped into stylized "fuel models" that include the variables important for combustion. Fuel models for predicting surface fire spread were developed by Rothermel (1972) and adapted for predicting fire behavior by Albini (1976) and for assessing fire danger by Deeming et al. (1977). Anderson (1982) provided aids for determining fuel models for estimating fire behavior and showed how the models in the two systems were similar. The Albini (1976) and Deeming et al. (1977) models contained the necessary fuel information for calculating reaction intensity and rate of spread. However, the two systems use different algorithms for determining characteristic values to be representative of the entire fuel array. The fire behavior system uses the surface area to volume ratio for weighting, whereas the danger rating system uses fuel load. Rothermel's (1972) surface fire spread model was not designed to predict crown fire spread, account for the large fuels that burn after the fire front goes by, or predict fire effects such as duff consumption and smoke production.

Acknowledging these limitations of existing fuel models, Sandberg et al. (2001) proposed a new system of fire characteristic classes that would provide all the information necessary for predicting fire behavior, fire danger, and fire effects. Fuel characteristic classes are defined for a vegetation type and contain data for fuels in up to six strata representing potentially independent combustion environments. For example, a ponderosa pine *(Pinus ponderosa)* type might have fuels in the tree canopy, shrub, woody fuel, and ground fuel strata. A stratum can contain one or more fuelbed categories that contribute available biomass and flammable surfaces to the stratum. Continuing with the ponderosa pine example, there might be overstory and understory categories in the tree stratum, and sound wood, rotten wood, and snags in the woody fuel stratum. The physiognomy of each fuelbed category determines a set of morphological, chemical, and structural features that define a fuelbed component (Sandberg et al. 2001). Fuelbed components combust differently and have a unique influence on fire behavior and effects. Examples of fuelbed components include the different size classes of sound woody fuels and the foliage and twigs of shrubs. Each component is defined by a set of quantitative variables that specify physical, chemical, and structural characteristics of the fuelbeds.

TREE CANOPY FUELS

The tree canopy stratum contains understory and overstory fuel that lead to and sustain crown fires. Continuity in the vertical distribution of these fuels provides the avenue for fire to spread into the upper canopy. Quantitative variables for canopies include mean live crown base height, mean canopy height, canopy bulk density, and percent cover. Low live crown bases and the presence of understory trees contribute to *ladder fuels* that allow a fire to reach into the upper crowns. The bulk density of the crowns, measured in kg m^{-3} (lb ft^{-3}), directly affects crown fire spread. Percent cover relates to the spatial homogeneity of the canopy stratum and affects subcanopy wind speeds and fuel shading.

SHRUB FUELS

The shrub stratum is described by height to live crown base, mean shrub height, the live to dead ratio, and percent cover. The heat content, moisture of extinction, surface area to volume ratio, and load by size class of the live leaves and twigs and the dead twigs and branches are additional variables that need to be quantified. Of all of these variables, the mean shrub height and total fuel load are the most important determinants of fire behavior. Chaparral fires in southern California become very intense because of their heavy loads and near-optimum compactness.

LOW VEGETATION FUELS

Low vegetation fuels include grasses, sedges, and forbs. These fuels are classified by their surface area to volume ratio and whether they are annuals or perennials. Mean height, load, percent cover, and maximum percent that can be live are the quantitative variables that describe grasses and sedges. Mean height and load affect the packing ratio, and percent live affects the ratio between live and dead herbage and, consequently, their moisture content.

WOODY FUELS

Sound logs, rotten logs, snags, and stumps are included in the woody fuel stratum. Sound woody fuel is divided into components that correspond to the moisture timelag classes with the addition of a greater than 22.86 cm (9 in) component. For each of these components, a load, surface area to volume ratio, fuelbed depth, heat content, and moisture of extinction need to be specified. Sound wood particles less than 7.62 cm (3 in) in diameter contribute to spread of the flaming fire front, roughly in proportion to their corresponding surface area to volume ratios. Although the larger fuels are ignited by the flaming front, they do not contribute to surface fire spread. Instead, they burn or smolder for hours or days and their heat and emissions are instrumental in producing fire effects such as tree mortality and smoke. The rotten wood category includes wood in the advanced rot stage that usually does not burn with the passing of the flaming front but smolders afterwards, contributing to smoke and other emissions. Snags are standing dead trees that, once ignited, produce firebrands. These burning embers can be lofted into the air and carried down wind, starting spot fires. Snags are classified by class, diameter, and height.

LITTER FUELS

Litter fuels include moss, lichen, needles, or leaves, and all can contribute to the spread of the fire front. Physiognomic variables for litter fuels include moss type, litter type, and litter arrangement. Percent cover and mean depth are used to infer the biomass of these fuels.

GROUND FUELS

The ground fuel stratum is divided into upper duff, lower duff, basal accumulation, and animal middens fuelbed categories. The upper duff is defined as the weathered or fermentation layer, whereas the lower duff component consists of the humus or decomposed layer. Both duff components contribute to emissions and smoke and are measured by their depth, load, and percent of rotten wood. The accumulation of fuel occurs in middens or around the bases of large trees and can become very deep and smolder for days, generating enough heat that can kill the tree through cambium mortality and loss of fine root hairs.

Fire Weather

Simply having enough fuel on the ground is not sufficient to produce a fire; an ignition source must be present to start a fire, and weather conditions must be such that the fire will continue to spread once ignited. As we learned in the previous chapter, weather is the state of the atmosphere surrounding the earth and the atmosphere's changing nature (Schroeder and Buck 1970). Fire weather is concerned with weather variations within the first 8–16 km (5–10 mi) above the earth's surface that influence wildland fire behavior. Fire weather includes air temperature, atmospheric moisture, atmospheric stability, and clouds and precipitation.

Air Temperature

Ambient air temperature affects fuel temperature, which is one of the key factors determining when fires start and how they spread (Schroeder and Buck 1970). The amount of heat necessary to evaporate the fuel moisture and raise the temperature of the fuel to the ignition point is directly related to the initial fuel temperature and the temperature of the air. As the air temperatures rise, less heat is required. As discussed in the section on fuel moisture timelag classes, these processes can take only seconds for fine fuels and minutes to hours for large fuels. Fire effects such as scorch height are also affected by air temperature. Air temperature indirectly affects fire behavior through its influence on other factors such as winds, atmospheric moisture, and atmospheric stability.

Atmospheric Moisture

Moisture in the air is one of the key elements of fire weather (Schroeder and Buck 1970). Atmospheric moisture directly affects fuel moisture and is indirectly related to other fire weather factors such as thunderstorms and lightning. The maximum amount of moisture that can be held in air is directly related to the air temperature and the atmospheric pressure. At a given pressure, as temperature rises, more water vapor can be held. The actual amount of water vapor in the air is called the *absolute humidity.* The ratio between the actual amount and the maximum amount at any particular temperature and pressure is called the *relative humidity.* There is a continuous exchange of water vapor between the air and dead fuels. Fuel gives off moisture when the relative humidity is low. The exchange continues until the equilibrium moisture content is reached. Fuels absorb water vapor when the relative humidity is higher than the fuel moisture content and give off moisture when the relative humidity is lower. The rate of exchange is related to the difference between the air and fuel moisture contents and the surface area to volume ratio of the fuels. Extremely low relative humidity can also affect live fuel moisture content as plants transpire increasingly more water vapor as temperature increases.

Atmospheric Stability

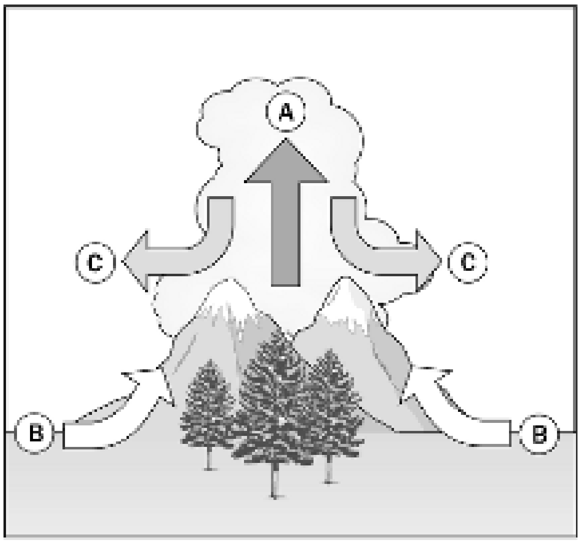


FIGURE 3.3. Under conditions of atmospheric instability, heat from the fire rises to form an updraft (A), causing an indraft of air near the surface (B). As the column collapses, strong downdraft winds can blow the fire in several directions (C).

Fire behavior is greatly affected by atmospheric motion and the properties affected by that motion (Schroeder and Buck 1970). Surface winds are the most obvious result of differences in atmospheric pressure as air moves from areas of high pressure to areas of low pressure. Vertical motions within the atmosphere can have dramatic effects on fire behavior. Heat from the fire generates vertical motion near the surface and creates a convective column that is affected directly by the stability of the air (Schroeder and Buck 1970). Unstable air allows the convection column to grow, causing an indraft into the fire at the surface and eventually leading to a downdraft as the column collapses (Fig. 3.3). These winds can cause erratic and severe fire behavior. Ironically, unstable air provides the best conditions for dispersing smoke into the atmosphere. Subsidence of air from high-pressure areas to low-pressure areas brings with it strong hot and dry winds caused by air moving across a steep pressure gradient. The Santa Ana in southern California and the Mono in the Sierra Nevada are well-known examples of gradient winds that have an extreme effect on fire behavior.

Wind Speed and Direction

Of all the weather or weather-related factors affecting fire behavior, winds are the least predictable and the most variable. Winds affect fire behavior by carrying away moisture in the air, thereby drying the fuels, and by increasing the oxygen supply and accelerating combustion. This is the reason we blow on a campfire in order to get it going—more oxygen, faster combustion. Gradient and frontal winds are associated with pressure differences and movements of large air masses. The passage of a dry cold front can cause strong, gusty winds and dry, unstable air. Local heating and cooling and the shape of the topography affect convective winds near the earth's surface. For example, up-canyon winds in the morning and down-canyon winds in the evening are the result of differential heating and cooling of terrain surfaces. Fire spread is enhanced by transferring heat by convection and by bending the flames closer to the fuel. Embers from torching trees and burning snags are carried by the wind, starting spot fires ahead of the main fire and increasing its lineal and areal rate of growth.

Clouds and Precipitation

Clouds and precipitation affect fire behavior primarily through their effects on fuel moisture. Shade from clouds lowers the air temperature and raises the relative humidity. As a result, fuel temperature decreases and fuel moisture content increases. Thunderstorm clouds, however, can portend unstable atmosphere, erratic winds, and severe fire behavior. The amount of precipitation and its seasonal distribution determine the beginning, ending, and severity of the fire season (Schroeder and Buck 1970). Precipitation has the direct effect of raising fuel moisture.

Ignition

Now that we have an abundant array of fuel available for burning and fire weather conducive to fire spread, all we need is an ignition. Lightning and humans are the primary ignition sources, although volcanoes ignite fires when their infrequent eruptions occur. Not all ignitions result in a fire, however, because several conditions must be met before an ignition can become a fire and spread.

Ignition Sources

Lightning develops in thunderstorms that form as a result of frontal activity or air mass movements (Schroeder and Buck 1970). Thunderstorms associated with fronts occur when warm, moist air is forced over a wedge of cold air. Lightning is usually more prevalent with cold-front thunderstorms. Orographic lifting of air masses is also a common cause of thunderstorms and lightning as air moves over mountain ranges. As a thunderstorm develops, positive charges accumulate in the top of the cloud and negative charges in the lower portion. Lightning occurs in thunderstorms when the electrical energy potential builds up to the point that it exceeds the resistance of the atmosphere to a flow of electrons between areas of opposite charge (Schroeder and Buck 1970). Cloud-to-ground lightning accounts for about one third of all strikes, and these strikes are primarily negative (Fuquay 1982). Ignitions occur when the lightning strike has a long continuing current, as do approximately 80% of positive strikes and 10% of negative strikes. Lightning is pervasive in the state of California but is most prevalent in the mountains and the southeastern deserts. The temporal and spatial distribution of lightning strikes is discussed in Chapter 2.

Native Americans have been cited as an ignition source for fires throughout California (Anderson 1996). Their fires were set for many reasons including nurturing plants used for food such as California black oaks *(Quercus kelloggii)*, enhancing the quality of plants shoots used in basketry, clearing vegetation around village sites, and driving game for easier hunting. Anderson (1996) states that some ecosystems can be labeled anthropogenic because they were probably dependent on human activities for their perpetuation. Examples of this practice are patches of deer grass in chaparral, montane meadows, desert fan-palm oases, coastal prairies, and oak woodlands. Although fires set by Native Americans certainly burned areas occupied or used by them, the areal extent of those fires remains uncertain. In the chapter *Use of Fire by Native Americans* (Chapter 17), Anderson states that their use spanned a gradient from intensive use to no use at all. Vale (1998) suggests that non-human processes determined the landscape characteristics of over 60% of Yosemite. In these areas there were scattered Native American camps and few, if any, fires. For the remaining 40%, Vale (1998) states that there were more frequent fires that were possibly made more numerous by ignitions by Native Americans, and that around village sites, fires were likely to be more frequent as a result of their fires. In all likelihood, ignitions by Native Americans were an addition to lightning ignitions rather than a substitute for them, and the landscape was a mosaic of both natural and cultural characteristics.

Ignition Probability

Not all ignitions result in a fire. Ignition by a lightning strike or a firebrand occurs in four stages (Deeming et al. 1977). First, contact with a receptive fuel must be made. Once contact is made, the moisture in the fuel must be driven off. The temperature of the fuel must then be raised to the point of pyrolysis. And finally, the gasses must be heated to ignition temperature. The probability that a firebrand will start a fire is a function of the fine dead fuel moisture (1-hour timelag fuel moisture) content; fuel temperature; surface area to volume ratio and packing ratio; and characteristics of the firebrand such as temperature, rate of heat release, length of time it will burn, and whether it is flaming or glowing (Deeming et al. 1977). In the fire behavior prediction system, ignition probability is calculated using fine dead fuel moisture, air temperature, and percent shading (Rothermel 1983). In addition to those three, the ignition component in the National Fire Danger Rating System includes the spread component in order to determine the probability of detecting an ignition that requires suppression action (Deeming et al. 1977).

Using simulated lightning discharges, Latham and Schlieter (1989) found that ignition probabilities for duff of short-needled conifers such as lodgepole pine *(Pinus contorta* ssp. *murrayana)* depend almost entirely on duff depth. Ignition of litter and duff from long-needled conifers including ponderosa pine and western white pine *(Pinus monticola)* was affected primarily by the moisture content. Ignition was also dependent on the duration of the arc, indicating that a lightning strike's length of time could have an effect on starting a fire.

Arnold (1964) found that only 25% of the lightning's long-continuing discharges actually started fires. In Yosemite National Park, the 7,250 lightning strikes that occurred from 1985 through 1990 produced 361 fires, an ignition rate of only 5% (van Wagtendonk 1994). Many discharges might have resulted in fires that did not grow large enough to be detected and went out before they could be located. Other discharges

TABLE 3.2

Fire types, fuel strata, and categories in which they burn

Fire Type	*Fuel Bed Stratum*	*Fuel Category*
Ground	Ground fuel	Duff, peat, basal accumulation, animal middens
Surface	Litter fuel	Litter, lichens, moss
	Woody fuel	Sound wood, rotten wood, piles and jackpots, stumps
	Shrub	Shrubs, needle drape
	Low vegetation	Grasses and sedges, forbs
Passive Crown	Litter fuel	Litter, lichens, moss
	Woody fuel	Sound wood, rotten wood, piles and jackpots, stumps
	Shrub	Shrubs, needle drape
	Low vegetation	Grasses and sedges, forbs
	Tree canopy	Canopy, snags, ladders
Active Crown	Litter fuel	Litter, lichens, moss
	Woody fuel	Sound wood, rotten wood, piles and jackpots, stumps
	Shrub	Shrubs, needle drape
	Low vegetation	Grasses and sedges, forbs
	Tree canopy	Canopy, snags, ladders
Independent Crown	Tree canopy	Canopy, snags, ladders

might have struck rock, snow, or other noncombustible substances. Deeming et al. (1977) combined ignition probability with rate of spread to an index for the chance that an ignition will result in a detectable fire.

Fire Behavior

Finally, we have the necessary ingredients for a fire: sufficient fuel, conducive weather, and an ignition. We now look at how these factors, combined with topography, cause a fire to spread. Fires can spread through ground fuels, surface fuels, crown fuels, or combinations of all three. Spot fires ignited by lofted firebrands can also spread fires. Each method has unique physical mechanisms necessary to sustain fire spread. The fuel stratum that is burned and the method of spread define fire types (Table 3.2). Ground fires burn the duff or other organic matter such as peat and usually burn with slow-moving smoldering fires, often after the surface fire as passed. Surface fires burn the litter, woody fuels (up to 7.62 cm [3 in]), and low vegetation such as shrubs, with and active flaming front. *Passive* crown fires burn surface fuels and single trees or groups of trees, *active* crown fires burn in the canopies in conjunction with a surface fire, and *independent* crown fires spread through the canopies without a surface fire.

Flaming Front

The flaming front is the area of the fire at its leading edge and is defined by its forward rate of spread, residence time, and flaming zone depth. These characteristics are used to calculate additional characteristics including reaction intensity, fireline intensity, flame length, and heat per unit of area. Equations for calculating these characteristics are included in Box 3.3. *Rate of spread* is the speed at which the flaming front moves forward and is measured in units of distance per unit of time. Rate of spread is affected by many fuel, weather, and topographic variables. The time the flaming front takes to pass over a point is called the *residence time*. The *flaming zone depth* is defined as the distance from the front to the back of the active flaming front and is calculated by multiplying the rate of spread by the residence time. Anderson (1969) found that the residence time was related to the size of the particles that were being burned.

The rate of energy release is characterized by the reaction intensity and the fireline intensity. *Reaction intensity* is the rate of energy release per unit of flaming zone area. The reaction intensity is the source of heat that keeps the chain reaction of combustion in motion and is a contributor to fire effects.

Fireline intensity is the rate of energy release per unit length of fire front and is likened to the amount of heat you would be exposed to per second while standing immediately in front of a fire. It is equivalent to the product of the available energy (in terms of heat per unit of area) and the forward rate of spread and can also be determined from reaction intensity and flaming zone depth (Box 3.3). Fireline intensity is related to flame length, the average distance from the base of the

BOX 3.3. EQUATIONS FOR THE FLAMING FRONT CHARACTERISTICS

Characteristic	Metric		English
Fireline Intensity(FLI)			
FLI = (Heat/Area) × Rate of Spread)/60	FLI	Kw m^{-1}	Btu ft^{-1} s^{-1}
	H/A	kJ m^{-2}	Btu ft^{-2}
	ROS	m min^{-1}	ft min^{-1}
FLI = (Reaction Intensity × Flaming Zone Depth)/60	FLI	Kw m^{-1}	Btu ft^{-1} s^{-1}
	RI	kJ m^{-2} min^{-1}	Btu ft^{-2} min^{-1}
	FZD	m	ft
FLI = (Reaction Intensity × Rate of Spread × Residence Time)	FLI	Kw m^{-1}	Btu ft-1 s^{-1}
	RI	kJ m^{-2} min^{-1}	Btu ft^{-2} min^{-1}
	ROS	m min^{-1}	ft min^{-1}
	RT	min	min
FLI = 258 × (Flame Length)$^{2.17}$	FLI	Kw m^{-1}	
	FL	m	
FLI = 5.67 × (Flame Length)$^{2.17}$	FLI		Btu ft^{-1} s^{-1}
	FL		ft
FLame Length (FL)			
FLame Length (FL)			
FL = 0.237 × (Fireline Intensity)$^{0.46}$	FL	m	
	FLI	Kw m^{-1}	
FL = 0.237 × (Fireline Intensity)$^{0.46}$	FL		ft
	FLI		Btu ft^{-1} s^{-1}
Heat per Unit Area (H/A)			
H/A = (60 × Fireline Intensity)/Rate of Spread	H/A	Kw m^{-2}	Btu ft^{-2}
	FLI	Kw m^{-1}	Btu ft^{-1} s^{-1}
	ROS	m min^{-1}	ft min^{-1}

ROS = Rate of Spread; RI = Reaction Intensity, FZD = Flaming Zone Depth, RT = Residence Time

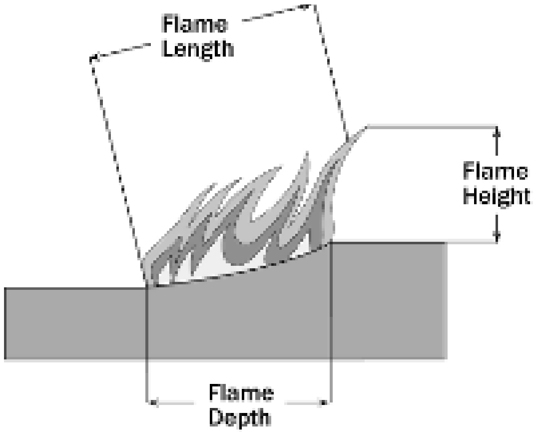


FIGURE 3.4. Flame dimensions for a wind-driven fire. Flame length is related to the fireline intensity and is measured from the base of the flame to its tip.

flame to its highest point. Figure 3.4 shows flame dimensions with flame length as the hypotenuse and flame height the vertical distance to the highest point.

Byram (1959) provided the approximate relationship between fireline intensity and flame length (Box 3.3). His equations can be reversed to obtain simple expressions for fireline intensity in terms of flame length. Byram (1959) cautioned that the equations for fireline intensity based on flame length are better approximations for low-intensity fires rather than for high-intensity fires. Although not without its difficulties, flame length is the only measurement that can be taken easily in the field that is related to fireline intensity (Rothermel and Deeming 1980).

Available fuel energy is the energy that is actually released by the flaming front, while *total* fuel energy is the maximum energy that *could* be released if all the fuel burns. Energy release is measured in heat per unit of area and can be

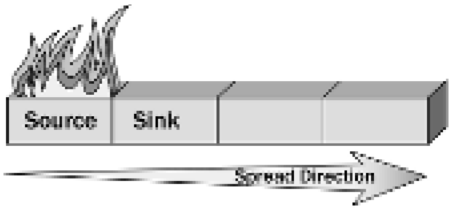


FIGURE 3.5. Rate of spread is the ratio between the heat source and the heat sink. As more heat is generated by the source, the more quickly the heat sink ignites.

calculated from the fireline intensity and the rate of spread (Box 3.3). Heat per unit area is the primary contributor to fire effects since it is independent of time.

Surface Fire Spread

The first attempt to describe fire spread using a mathematical model was by Fons (1946). He theorized that because sufficient heat is needed at the fire front to ignite adjacent fuels, fire spread is a series of successive ignitions controlled by ignition time and the distance between fuel particles. Conceptually, this is analogous to viewing a fuelbed as an array of units of volume of fuel, each unit being ignited in turn as its adjacent unit produces enough heat to cause ignition. The unit being ignited is the *heat sink,* whereas the unit currently burning is the *heat source* (Fig 3.5).

Frandsen (1971) developed the first theoretical model of this process by applying the conservation of energy principle to a unit volume of fuel ahead of a fire front. The unit of fuel that is currently burning serves as the heat source for the unit ahead which acts as a heat sink. Sufficient heat must be generated by the source to ignite the adjacent unit. The rate of spread is determined by the rate at which adjacent fuel units are ignited.

The equation for Frandsen's (1971) quasi—steady-state rate of spread in uniform fuels is shown in (Box 3.4). The numerator is the heat source and contains two terms, one for the horizontal propagating heat flux (I_{xig}) and another for the gradient of the vertical intensity flux ($([\delta Z_c/\delta Z]z_c)$). The horizontal flux is a measure of the heat received by the adjacent fuel unit through internal convection and conduction and through radiation from the vertical flame. The gradient flux measures the additional heat received through flame contact, convection, and radiation as the slope or wind brings the flame closer to the adjacent unit. The denominator is the heat sink and contains two terms, one for the effective bulk density of the adjacent fuel, which is the proportion of that fuel that actually ignites (ρ_{be}), and one for the heat necessary to bring it to ignition (Q_{ig}). The proportion that ignites is a function of fuel particle size: the smaller the particle, the greater the proportion that burns. For example, once a large log starts burning, only the outer portion has been raised to ignition temperature. The result of the interaction of the numerator and the denominator in the equation is that fire spreads faster as more heat is produced but spreads slower as it becomes necessary to ignite greater quantities and sizes of fuel.

BOX 3.4. FRANDSEN'S (1971) EQUATION FOR QUASI–STEADY STATE RATE OF SPREAD

$$R = \frac{I_{xig} + \int_{-\infty}^{0} \left(\frac{\partial Zc}{\partial Z}\right)_{z_c} dx}{\rho_{be} Q_{ig}}$$

where

R = quasi–steady state rate of spread
I_{xig} = horizontal propagating heat flux
$\left(\frac{\partial Zc}{\partial Z}\right)_{z_c}$ = gradient of the vertical intensity flux
ρ_{be} = effective bulk density
Q_{ig} = heat of pre-ignition

Because some of the terms in Frandsen's (1971) equation contained unknown heat transfer mechanisms, Rothermel (1972) devised experimental and analytical methods to determine these terms using fuel, weather, and topographic variables. His model of surface fire spread has been the most commonly used model in the United States since the mid-1970s. The first predictions using Rothermel's (1972) methods were made with the nomograms contained in Albini (1976). Procedures for field use of handheld calculator versions of the model were developed by Burgan (1979) and Sussott and Burgan (1986). Rothermel (1983) formalized the procedures for training fire behavior analysts to use the spread model for use on wildland fires. The model was subsequently computerized by Andrews (1986) in the BEHAVE fire prediction and fuel modeling system. The advent of laptop computers made it possible to combine the fire spread model with other fire behavior models into the FARSITE model, which performs simulations of areal fire spread (Finney 1998). Attempts are under way in Australia to refine the surface spread model, but results are not yet complete.

Box 3.5 shows the surface fire spread equation and defines each of its terms. In the numerator, the propagating fluxes were divided into terms that accounted for the total heat release, the proportion of the heat reaching the adjacent fuel unit, and wind and slope effects. Using the campfire analogy, the total heat release is all of the heat produced by the fire, whereas the heat reaching you sitting at the fire's side would be the proportion reaching the adjacent fuel. Imagine how much hotter you would become if you were able to sit while hovering just above the fire. In the denominator, empirical relationships were used to define bulk density, the effective heating number, and the heat of pre-ignition. The final formulation provided an approximate solution to the equation (Burgan and Rothermel 1984). Each of the terms in the surface

BOX 3.5 THE ROTHERMEL (1972) SPREAD EQUATION

$$R = \frac{I_R\, \boldsymbol{\xi}\, (1 + \Phi_w + \Phi_s)}{\rho_b\, \varepsilon Q_{ig}}$$

where

R = forward rate spread of the flaming front, measured in m min^{-1} (ft min^{-1})
I_R = reaction intensity, a measure of the energy release rate per unit of area of flaming front, in kJ m^{-2} min^{-1} (Btu ft^{-2} min^{-1})
ξ = propagating flux ratio, the proportion of the reaction intensity reaching the adjacent fuel, dimensionless
Φ_w = wind coefficient, which accounts for the effect of wind increasing the propagating flux ratio, dimensionless
Φ_s = slope coefficient, a multiplier for the slope effect on the propagating flux ratio, dimensionless
ρ_b = fuelbed bulk density, a measure of the amount of fuel per unit of volume of the fuelbed, measured in kg m^{-3} (lb ft^{-3})
ε = effective heating number, the proportion of the fuel that is raised to ignition temperature, dimensionless
Q_{ig} = heat of pre-ignition, which is the amount of heat necessary to ignite 1 kg (1 lb) of fuel, measured in kJ kg^{-1} (Btu 1b^{-1})

BOX 3.6. THE EQUATION FOR REACTION INTENSITY (FROM ROTHERMEL 1972)

$$I_R = \text{э}'\, W_n\, h\, 0_m\, 0_s$$

where

I_R = reaction intensity, in kJ m^{-2} min^{-1} (Btu ft^{-2} min^{-1})
э = optimum reaction velocity, measured in min^{-1}
W_n = net fuel loading, in kg m^{-2} (1b ft^{-2})
h = low heat content, in kJ kg^{-1} (Btu 1b^{-1})
0_M = moisture damping coefficient, dimensionless
0_s = mineral damping coefficient, dimensionless

fire spread equation will be examined individually to gain insight into the complex effects of fuels, weather, and topography on surface fire spread. First we cover the terms in the numerator and then the terms in the denominator.

Reaction intensity (I_R) is made up of several factors explained below that relate to the rate of energy release (Box 3.6). Reaction velocity (э′) is a ratio that expresses how efficiently the fuel is consumed compared to the burnout time of the characteristic particle size (Burgan and Rothermel 1984). This ratio is a function of the actual and optimum packing ratios and the surface area to volume ratio. The actual packing ratio is found by dividing the fuelbed bulk density by the oven-dry fuel particle density. Albini (1976) specifies a standard value of 51.25 kg m^{-3} (32 lb ft^{-3}) for fuel particle density. The optimum packing ratio is a function of the surface area to volume ratio. Fine fuels, such as grass and long-needled pine litter, have near-optimum packing ratios and large surface area to volume ratios. These fuels burn thoroughly in a short period of time and have the highest reaction velocity.

The net fuel loading (w_n) is equal to the oven-dry fuel loading multiplied by 1 minus the fuel particle total mineral content (Albini 1976). Because minerals do not contribute to combustion, their weight must be removed from the calculation of reaction velocity. A mineral content value of 5.55 % is used for all standard fuel models.

The low heat content (h) provides the heat necessary to sustain combustion. There is some variation in heat content for fuels of different species. Conifers tend to have higher values than do hardwoods because of the presence of resins and higher lignin content. Sclerophyllous shrubs contain oils and waxes in their leaves that increase their heat content. Albini (1976) uses a standard value of 18.61 MJ kg^{-1} (8,000 Btu lb^{-1}).

The moisture damping coefficient (0_M) and mineral damping coefficient (0_s) account for the effects that moisture and minerals have in reducing the potential reaction velocity (Rothermel 1972). The moisture damping coefficient is derived from the fuel moisture content and the fuel moisture content of extinction, which is the moisture level at which combustion can no longer be sustained. The mineral damping coefficient is a function of the silica free ash content, termed the *effective* mineral content. A value of 1.00% is used for the standard fuel models (Albini 1976).

The proportion of heat reaching adjacent fuel is calculated under the assumption that the fire is burning without any wind and on flat terrain (Burgan and Rothermel 1984). The propagating flux ratio (ξ) is a dimensionless fraction that accounts for the fact that not all of the reaction intensity reaches adjacent fuels. For example, in the no-wind, no-slope situation pictured in Figure 3.6, most of the heat energy moves upward by convection, whereas only a smaller proportion is directed at the adjacent fuel by radiation and convection. The minimum value for the flux ratio is zero when no heat reaches adjacent fuels, and the maximum value is 1 when all the heat reaches adjacent fuels. These extreme values are seldom reached, and a more practical range would be from 0.01 to 0.20 because most of the heat is convected upward.

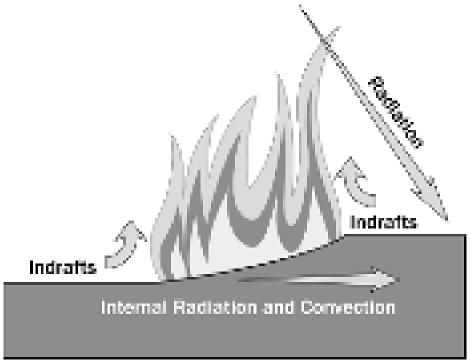


FIGURE 3.6. Under no-wind, no-slope conditions, heat is transferred by radiation from the flame and by internal radiation and convection. Indrafts move air up into the flame.

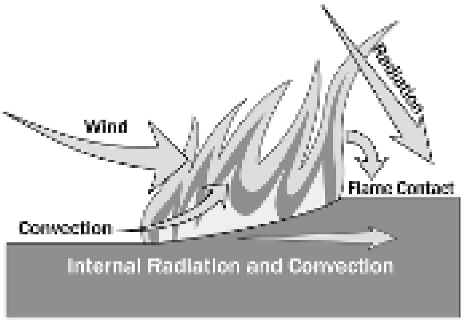


FIGURE 3.7. Under no-slope conditions, wind bends the flame closer to the adjacent fuel resulting in increased radiation, convective heat, and flame contact.

The surface area to volume ratio andthe the packing ratio are the determinants of the propagating flux ratio. As these two ratios increase, the flux ratio increases, with fine fuels having the most pronounced effect.

Both the wind coefficient (Φ_w) and the slope coefficient (Φ_s) have the effect of increasing the proportion of heat reaching the adjacent fuel. They act as multipliers of the reaction intensity. In the no-slope case, the wind coefficient increases rapidly with increases in wind speed in loosely packed fine fuels (Burgan and Rothermel 1984). Direct contact and increased convection and radiation heat transfer occur as the flame tips toward the unburned fuel (Fig. 3.7). Although the smoke might have caused you to move away from the campfire first, if you had remained, you would have felt the added heat from the closer flames. The wind coefficient is affected by surface area to volume ratio, packing ratio, and wind speed. Finer fuels have more surface area exposed to the increased radiation than do coarse fuels. Increasing the surface area to volume ratio increases the wind coefficient, and this effect becomes greater at higher wind speeds as the distance between the flame and the fuel decreases (Burgan and Rothermel 1984). The wind effect is less pronounced as the packing ratio moves beyond the optimum, and fuel particles begin to obstruct the convective flow. There is a maximum wind speed beyond which the wind coefficient does not increase (Burgan and Rothermel 1984). At that point, the power of the wind forces exceeds the convective forces. This occurs when the wind speed in km h^{-1} is twice the reaction intensity in kJ min^{-1} m^{-2} (or the wind speed in mi h^{-1} is 1/100 of the reaction intensity in Btu ft^{-2} min^{-1}). For typical annual grass fires with sparse fuels, wind speeds in excess of 19 km h^{-1} (12 mi h^{-1}) will not increase the rate of spread. In tall grasses, rate of spread will not increase after wind speeds reach 68 km h^{-1} (42 mi h^{-1}).

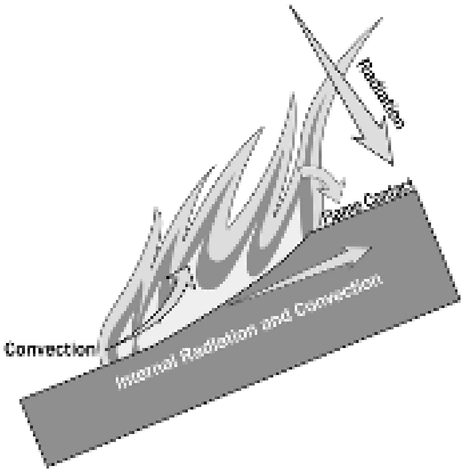


FIGURE 3.8. Under no-wind conditions with a slope, the convection component is not as pronounced as it would be with wind. Radiation and flame contact are still important factors for increasing spread.

Under no-wind conditions, the slope coefficient increases as the slope becomes steeper. The effect is similar, but less pronounced, than that of wind. Although flames are brought closer to the unburned fuels, without wind to bring heated air in contact with the fuel, there is only a slight increase in convection (Fig. 3.8). If you are standing above a fire on a slope, you will feel much hotter than if you were standing below. The packing ratio and the tangent of the slope are used to calculate the slope coefficient. The packing ratio has a slight influence on the sensitivity of the coefficient to increases in slope steepness (Burgan and Rothermel 1984). This effect is small in comparison to the other effects due to changes in the packing ratio. The wind and slope coefficients do not interact, but their combination can have a dramatic effect on fire behavior.

Now we take a look at the terms in the denominator of the Rothermel (1972) spread equation that constitute the heat sink. The denominator represents the amount of heat necessary to bring the fuel up to ignition temperature. The first term is *fuelbed bulk density* (ρ_b), the total amount of fuel that is potentially available. It is defined as the oven-dry weight of the fuel per unit of fuelbed volume and is calculated by dividing the oven-dry fuelbed load by the fuelbed depth. Because bulk density is in the denominator of the spread equation, an increase in density will tend to cause a decrease in spread rate (Burgan and Rothermel 1984). This can happen by either increasing the fuel load or by decreasing the fuelbed depth. However, an increase in load also causes the reaction intensity to increase. In addition, an increase in bulk density can cause the propagating flux and the wind and slope coefficients to go up or down depending on the relative packing ratio.

Not all of the fuel that is available will burn with the passing of the flaming front. Often only the outer portion of a large log or other fuel particle is heated to ignition temperature. The effective heating number (ε) defines the proportion of the fuel that will burn as the flaming front passes and is dependent on fuel particle size as measured by the surface area to volume ratio. Small particles will heat completely through and ignite, whereas decreasing proportions of larger particles will ignite as size increases. Not only do the thinner particles heat all the way through, but also their increased surface area allows heating by radiation to occur rapidly. Multiplying the fuelbed bulk density by the effective heating number yields the amount of fuel that must be heated to ignition temperature (Burgan and Rothermel 1984).

How much heat is required? The heat of pre-ignition quantifies the amount of heat necessary to raise the temperature of a 1-kg (2.2-lb) piece of moist fuel from the ambient temperature to the ignition point. First the moisture must be driven off and then the fuel must be heated. Most of these temperature values are fairly constant and can be calculated in advance (Burgan and Rothermel 1984). Moisture content does vary and is used to calculate the heat required for ignition. As fuel moisture content increases, there is a steady increase in the heat of pre-ignition. The units are in kJ kg^{-1} (Btu lb^{-1}). The product of the fuelbed bulk density, effective heating number, and the heat of pre-ignition is the heat per unit of area in kJ m^{-2} (Btu ft^{-2}) necessary to ignite the adjacent fuel cell.

Crown Fire Spread

A crown fire occurs when the fire moves from the surface fuels into the canopies of trees. Although shrub canopies can be considered crowns, the models developed for predicting crown fire behavior are specific to trees. Van Wagner (1977) defined three stages of crown fire. The first stage of crowning is a *passive* crown fire, which begins with the torching of trees from a surface fire. If the fire spreads through the crowns in conjunction with the surface fire, it is called an *active* crown fire. A crown fire spreading through the crowns far ahead of or in the absence of the surface fire is an *independent* crown fire.

FIGURE 3.9. Passive crown fires can occur under conditions of low crown base heights, even with relatively low wind speeds and low crown bulk densities.

In a passive crown fire, single trees or groups of trees torch out and there might be some movement of fire into adjacent tree crowns (Fig. 3.9). Torching can occur at low wind speeds with relatively low crown bulk densities if the crown bases are low enough to be ignited by the surface fire. Although a passive crown fire does not spread from crown to crown, embers from torching trees can start fires ahead of the fire front. Transition to passive crowning begins when the fireline intensity of the surface fire exceeds that necessary for igniting the crowns. This point is dependent on the height to the base of the live crowns and the foliar moisture content (Alexander 1988). Ladder fuels are considered in the calculation of the crown base height. Under conditions of low foliar moisture content, the crowns will ignite when the surface fire intensity is great enough to bring the crowns to ignition temperature either through direct contact with flames or through convective heat. Once ignited, the fire in the crowns will spread some, but, as long as the actual rate of spread of the crown fire is less than the threshold for active crown spread, the fire will remain passive. Actual spread rate can be calculated from surface fire spread rate, the proportion of the trees that are involved in the crowning phase, and the maximum crown fire spread rate (Rothermel 1991).

An active crown fire can occur when winds increase to the point that flames from torching trees are driven into the crowns of adjacent trees (Rothermel 1991). The heat generated by the surface fire burning underneath the canopy sustains the fire through the crowns (Fig. 3.10). The fire becomes a solid wall of flame from the surface to the crown and spreads with the surface fire (Scott 1999). Lower crown base heights, higher wind speeds, and higher crown bulk densities than those necessary for passive crowning are required for active crowning. The threshold for transition from passive to active crowning is dependent on the crown bulk density and a constant related to the critical mass flow through the canopy necessary for a continuous flame (Alexander 1988). Active crowning continues as long as the surface fire intensity exceeds the critical intensity for initiation of crown fire, and the actual spread rate, as calculated from the Rothermel (1972) equation, is greater than the critical crown fire spread rate. The critical spread rate for active crowning decreases rapidly as crown bulk density increases from 0.01 to 0.05 kg

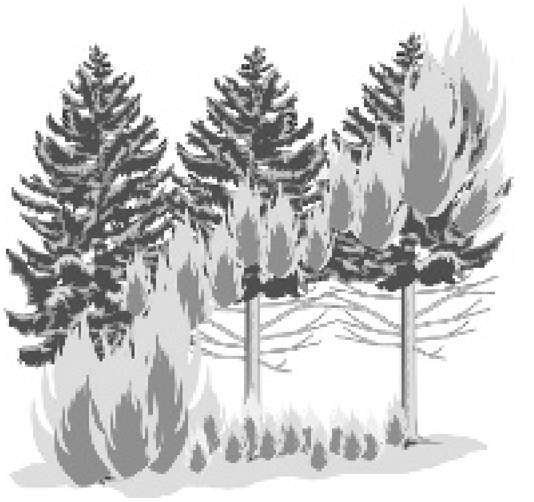


FIGURE 3.10. Higher wind speeds and crown bulk densities with low crown base heights lead to active crown fires.

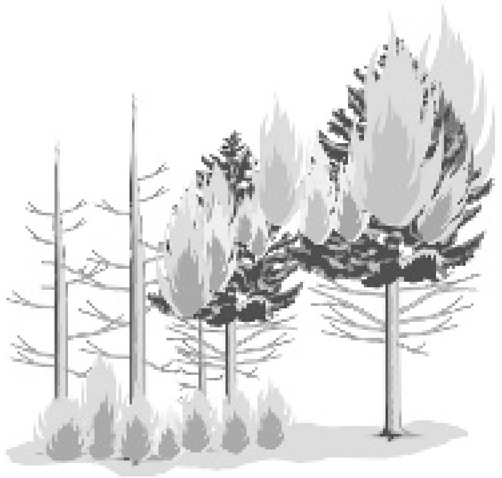


FIGURE 3.11. Very high wind speeds and crown bulk densities can lead to independent crown fires that race ahead of the surface fire.

m^{-3} (0.01–0.03 lb ft^{-3}). Consequently, the actual spread rate necessary to initiate crown fire spread becomes less (Scott 1999). As tree canopies become closer and denser, fire is able to spread more easily from tree to tree. After crown bulk densities reach 0.15 kg m^{-3} (0.09 lb ft^{-3}), there is little additional effect on the critical spread rate. Once an active crown fire is initiated, its intensity is calculated using the combined loading of the available surface fuels and crown fuels and the crown rate of spread (Finney 1998). The crown fuel loading is derived from the crown fraction burned, the mean canopy height, the crown base height, and the crown bulk density. The crown fraction burned is dependent on the critical surface spread associated with the critical intensity for initiating a crown fire (Van Wagner 1993).

Independent crown fires burn in aerial fuels substantially ahead of the surface fire and are rare, short-lived phenomena (Fig. 3.11). It is unlikely that these stand-replacing fires occurred over extensive areas during the past several centuries as evidenced by the lack of large areas of even-aged vegetation. Although Swetnam (1993) reported the occurrence of widespread fires from several locations in the Sierra Nevada in 1297, the fires were not severe enough to erase the fire scar record of their occurrence and were not likely to have been independent crown fires. Steep topography, very high wind speeds, and bulk densities greater than 0.05 kg m^{-3} (0.03 lb ft^{-3}) lend themselves to the extreme behavior of these wind-driven fires. Independent crown fires occur when the surface fire intensity exceeds the critical intensity, the actual rate of spread is greater than the critical rate of spread, and the actual energy flux is less than the critical energy flux for independent crown fires in the advancing direction. Finney (1998) did not model independent crown fires because of their ephemeral nature.

Independent crown fires can also occur under low wind and unstable air conditions. Rothermel (1991) describes fires under those conditions as *plume-dominated* fires. Byram (1959) introduced the concept of energy flow rates in the wind field and in the convection column above a line of fire to explain the behavior of plume-dominated fires. The power of the wind is the rate of flow of kinetic energy through a vertical plane of unit area at a specified height in a neutrally stable atmosphere (Nelson 1993). The wind energy is a function of the air density, the wind speed, the forward rate of spread of the fire, and the acceleration due to gravity. The power of the fire is the rate at which thermal energy is converted to kinetic energy at the same specified height in the convection column. It is calculated from the fireline intensity, the specific heat of air, and the air temperature at the elevation of the fire. When the power of the fire is greater than the power of the wind for a considerable height above the fire, extreme fire behavior can occur (Byram 1959). Both Byram (1959) and Rothermel (1991) give equations for the wind and fire power functions, and Nelson (1993) has generalized the equations for use with any applicable system of units.

Spotting

Trees that are ignited during any of the crown fire stages and snags ignited by any fire are sources of firebrands that could ignite spot fires. The spread of a fire is increased dramatically by ignition of numerous spot fires ahead of the flaming front. Albini (1979) developed a model for calculating spot fire distance from a torching tree and enhanced his original model to accommodate embers generated from wind-driven fires (Albini 1983). The model calculates the height to which an ember is lofted, the time it remains burning, and the distance it travels. Characteristics of the torching tree and embers, the intervening area, and the receiving fuelbed all determine the distance and probability of ignition of a new spot fire (Fig. 3.12). Large embers are not lofted as high nor do they travel as far as small embers. Therefore, they are often still burning by the time they can land and start spot fires. Small embers usually burn out before they can land.

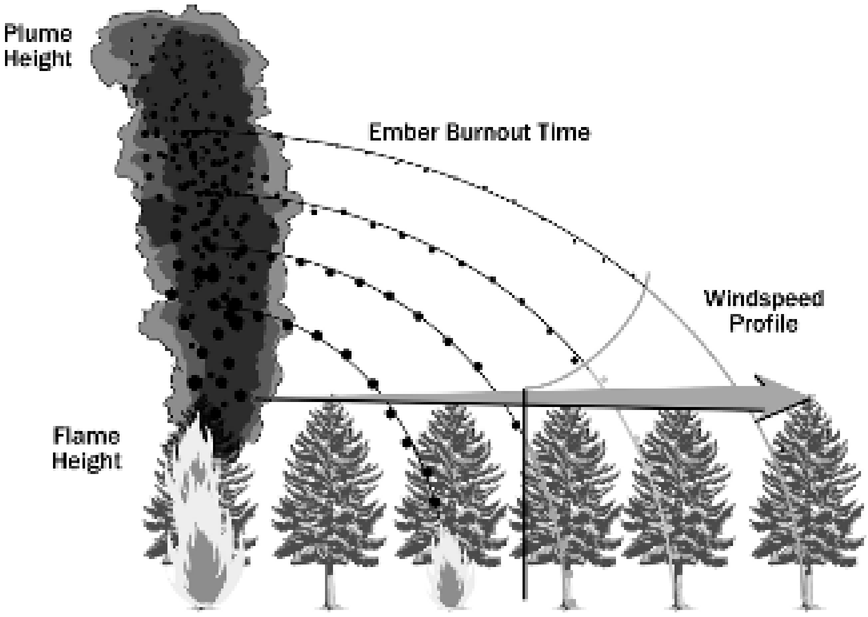


FIGURE 3.12. Large embers are not lofted as high as small ones but they remain lit long enough to ignite new spot fires. Small embers are lofted great distances but often are extinguished before they land. (Redrawn from Finney 1998.)

Tree species, height, and diameter, and number of torching trees in a group affect the flame height and time of steady burning. Ember characteristics include size, shape, density, and starting height in the tree. While the embers are in flight, the wind speed and direction, and the evenness and vegetative cover of the intervening terrain influence the distance traveled. If the ember lands on a receptive fuelbed, the fine fuel moisture and temperature determine whether a spot fire is ignited. Chase (1981, 1984) adapted the spot fire distance model for use in a programmable pocket calculator and it has been incorporated in BEHAVE (Andrews 1986) and FARSITE (Finney 1998).

Fire Effects

Once a fire is ignited, it starts to affect other components of the ecosystem. Plants, animals, soil, water, and air all interact in one way or another with fire. This section introduces the physical parameters of fire behavior that affect fire severity, spotting, tree scorch height, plant mortality, biomass consumption, and microclimate. The ecological ramifications of these effects are discussed in subsequent chapters.

Fire Severity

Fire severity is the magnitude of the effect that the fire has on the environment, and is commonly applied to a number of ecosystem components. We include in this definition fire effects that occur while the fire is burning over an area as well as those effects that occur in the post-fire environment. This differs from the definition used by burn area emergency rehabilitation (BAER) teams who use *fire* severity for the immediate fire environment and *burn* severity for post-fire environment (Jain 2004).

Different patterns of fire line intensity, fire duration, and the amount of dead and live fuel affect the level of fire severity. For example, a high-intensity fire of short duration could result in the same level of severity as a low-intensity fire of long duration. Furthermore, the same fire behavior can result in different severity effects to soils and understory and overstory vegetation. A high-intensity fire that moves quickly through the crowns may kill all of the trees but have relatively little effect on the soil, whereas a low-intensity fire might leave trees untouched but smolder for days and result in severe soil heating. Precise measures of severity will vary from one ecosystem to the next, depending upon the degree of change to biotic and physical ecosystem components.

Tree Crown Scorch Height

Scorch occurs when the internal temperature of the leaves or needles of a plant are raised to lethal levels. Both the temperature and its duration are important (Davis 1959). Exposure to temperatures of about 49°C (120°F) for an hour can begin to kill tissues, whereas temperatures of approximately 54°C (130°F) can kill within minutes, and temperatures over 64°C (147°F) are considered instantaneously lethal. Van Wagner (1973) related crown scorch height to the ambient air temperature, fireline intensity, and wind speed. Under conditions of warm air, less intensity is necessary to raise the tissue temperature to the lethal level (Fig. 3.13). For a given fireline intensity, scorch height is reduced sharply as wind speed increases. Winds cool the hot plume as entrained ambient air moves through the canopy (Albini 1976). Scorch height calculations are included in BEHAVE (Andrews and Chase 1989) and in FARSITE (Finney 1998).

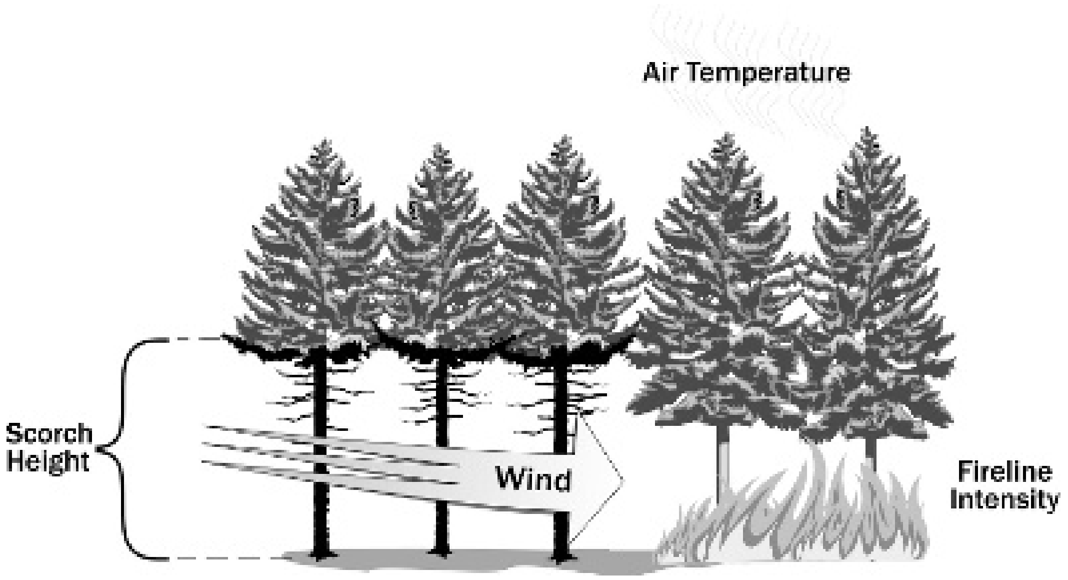


FIGURE 3.13. Scorch height is affected by fireline intensity, wind speed, and air temperature.

Plant Mortality

Mortality can occur when plants are either entirely consumed or certain tissues are raised to lethal temperatures for a sufficient duration. However, some species are able to sprout after complete canopy removal or scorch. For other species, if too much cambium or canopy is killed, the plant cannot survive. Ryan et al. (1988) studied long-term fire-caused mortality of mature Douglas-fir *(Pseudotsuga menziesii)* and found that the amount of cambium killed was the best predictor of tree mortality and that the percent of the crown scorch was a better predictor than was crown scorch height. Ryan et al. (1988) did not have flame length data available, but van Wagtendonk (1983) found that flame length was the best predictor of understory mortality of Sierra Nevada conifers. Peterson and Ryan (1986) used bark thickness, crown scorch height, and Rothermel's (1972) equation to predict cambial damage and mortality for northern Rocky Mountain species. Ryan and Reinhardt (1988) developed a model for predicting percent mortality based on percent volume crown scorch and bark thickness. Bark thickness was derived from species and diameter, while percent crown scorch was calculated from the scorch height, tree height, and crown ratio. Fire-induced mortality calculations based on their work is included in the FIRE 2 module of BEHAVE (Andrews and Chase 1989). Stephens and Finney (2002) found that mortality of Sierra Nevada mixed conifers was related to percent canopy scorched and local ground fuel consumption.

Biomass Consumption

The amount of biomass consumed by the flaming front can be calculated from the heat per unit of area released by the fire. Fire effects are often more related to the heat given off after passage of the flaming front, however. Van Wagner (1972) provided equations for estimating the amount of the combined litter and fermentation layers that would burn based on the average moisture content of those layers. Similar results for litter and duff layers in the Sierra Nevada were found by Kauffman and Martin (1989). They found that consumption of the litter and fermentation layers was inversely related to the moisture content of the lower duff layer. Albini et al. (1995) modeled burnout of large woody fuels including the influence of smoldering duff. The rate at which these fuels burn is a balance between the rate of heat transfer to the fuel and the amount of heat required to raise the fuel to a hypothetical pyrolysis temperature. CONSUME, a computer program developed by Ottmar et al. (1993), predicts the amount of fuel consumption on logged units based on weather data, the amount and fuel moisture of fuels, and a number of other factors.

Microclimate

The effect of fire on microclimate can be determined by comparing canopy densities before and after a fire. These secondary effects are manifested through changes in the vegetation. For example, a fire that thins a stand of trees will increase wind speed and temperature at the ground surface and decrease relative humidity and fuel moisture (Fig. 3.14). A more open canopy allows more sunlight to reach the surface fuels and offers less resistance to winds above the canopy. These changes will, in turn, affect the behavior of subsequent fires. The rationale for adjusting wind speed 6.5 m (20 ft) above the canopy to midflame wind speeds is given in Albini and Baughman (1979), and adjustment factors for various fuel models are given by Rothermel (1983). Rothermel et al. (1986) explain the procedures for modeling the moisture

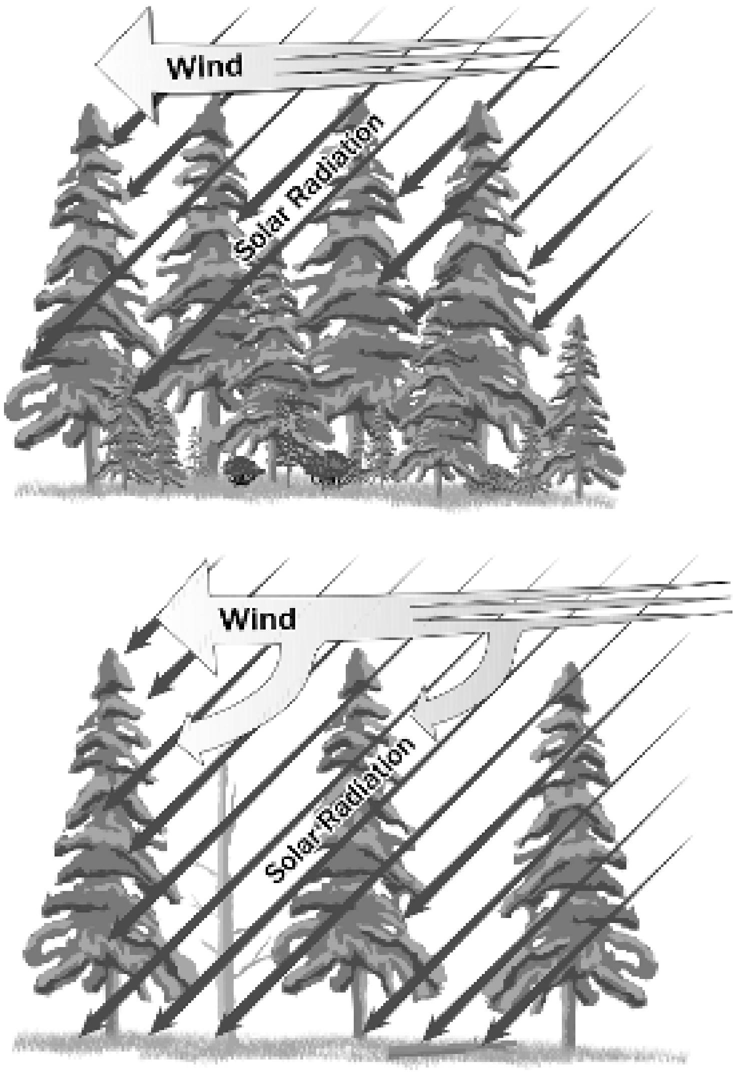


FIGURE 3.14. Solar radiation, temperature, and wind speeds are increased, and relative humidity is decreased after a fire has opened up a stand of trees.

content of fine dead fuels based on particle size, weather conditions, and exposure to sun and wind.

Summary

In this chapter we have covered fire as a physical process. A fire cannot occur unless there is sufficient fuel available to support combustion, weather conditions are conducive for burning, and an ignition source is present. Combustion is an oxidation process that combines hydrocarbons in the form of vegetative fuels with oxygen to produce carbon dioxide, water, and energy. This basic ecosystem process occurs in three phases: a preheating phase, a gaseous flaming phase, and a smoldering phase. Heat from combustion is transferred through conduction, convection, and radiation. Fuel characteristics determine the amount of fuel energy available and its rate of release. Fireline intensity is the rate of energy release per unit of length of fire front, and the reaction intensity is the rate of release per unit of area. Important fuel characteristics include the size of the fuels, their ability to absorb and release moisture, their compactness, and their total weight. Fuels are categorized into models that include all the various characteristics that affect fire behavior and fire effects. Strata that are included in these models are tree canopy fuels, shrub fuels, low-vegetation fuels, woody fuels, litter fuels, and ground fuels.

Fire weather is a critical determinant of fire behavior. Elements of primary importance are relative humidity, which affects fine-fuel moisture, and wind speed, which affects the rate of energy release and rate of spread. Strong wind or atmospheric instability can lead to severe fire behavior including crowning and spotting. Ignition sources include lightning, volcanoes, and humans. Air temperature and the fine-fuel moisture content determine whether an ignition results in a fire.

Once ignited, the fire begins to spread on the surface as the heat generated from a cell of fuel reaches the temperature necessary to ignite the adjacent cell. The heat source is generated by the heat content present in the fuel and is affected by the surface area to volume ratio, packing ratio, moisture content, and mineral content. Surface fire spread is accelerated by wind and steep topography. The heat sink is composed of the bulk density of the fuel of the adjacent cell, its surface area to volume ratio, and its moisture content. Crown fire spread occurs when the heat from the surface fire crosses the threshold necessary to ignite crowns. Factors affecting that threshold include the height to the live crown base, the foliar moisture content, and the crown bulk density. Torching trees can loft embers that ignite spot fires downwind from the main fire.

Fires affect vegetation by consuming complete plants or raising the temperature of live tissues to lethal levels. Consumption of fine fuels is related to the reaction intensity, whereas consumption of large fuels is influenced primarily by moisture content. Microclimate is affected indirectly through the effects of fire on vegetation.

Fire plays a dynamic role in natural ecosystems. As a physical process, it reacts to and influences other ecosystem components. The current physical and biological environments of California ensure that fire will continue to be present and that humans must learn to adapt to fire as part of that environment. In the following chapter, we will see how the physical process of fire is integrated within ecosystems as an ecological process.

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