5. Fire as a Dynamic Ecosystem Process

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Introduction

In the absence of some ecosystem process such as decomposition to oxidize accumulated organic material, 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 available fuel for the inevitable fire that will occur. All that is needed is an ignition source, weather conditions conducive to burning, and a sufficient amount of fuel. Once ignited, the fire will have differential effects on the vegetation depending on In this chapter we will look at fire as a physical process, fire in the context of ecological theory, the natural effects of fire on Sierra Nevada ecosystems, and natural and twentieth century fire regimes.

The physical process of fire

The physical process of fire begins with an ignition. That ignition must occur where there is sufficient fuel available for a fire to spread. Once ignited, the behavior of the fire will be determined by fuel characteristics, weather conditions, and topography.

Ignition

Ignition sources. Lightning develops in thunderstorms that develop 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 the most 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 is positively charged. These are the strikes that can lead to an ignition.

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; 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 since 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. Native American use of fire spanned a gradient from intensive us to no use at all. Vale (1998) suggests that non-human processes determined the landscape characteristics of over 60 percent of Yosemite. In these areas there were scattered Native American camps and few, if any, fires. For the remaining 30 percent, 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 in addition to lightning ignitions rather than a substitute for them and that the landscape was a mosaic of both natural and cultural characteristics.

Variation in time. Most fires occur between June through September.

Variation in space. Lightning is pervasive in the state of California but is most prevalent in the mountains. For example, during the 6-year period from 1985 through 1990, van Wagtendonk (1991) found that over 7,000 strikes occurred in the 302,700 ha (748,000 ac) of Yosemite National Park. The number of strikes per year ranged from a low of 530 in 1986 to a high of 2,016 in 1990. The spatial distribution also varied with fewer strikes than would be expected at elevations below 2,600 m (8,000 ft) and more than would be expected above that elevation. When calculated on a per area basis, the high elevations from 2,743 m to 3,048 m (9,000 ft to 10,000 ft) received nearly four times the number of strikes as the area from 610 m to 914 m (2,000 ft to 3,000 ft).

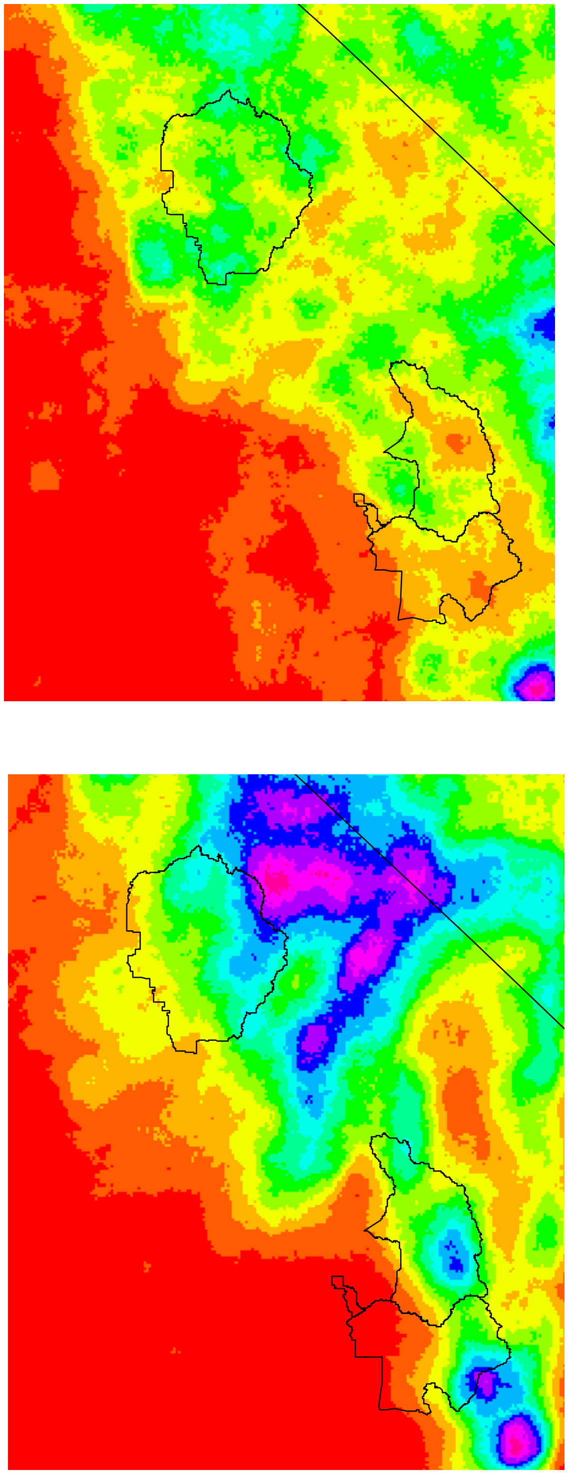


Figure 5.x. *Lightning strike density for the area between Yosemite, Sequoia and Kings Canyon*

National Parks, 1987-1990.

Fire weather

Simply having an ignition source is not sufficient to have a fire to support a fire regime. There must be enough fuel on the ground, and weather conditions must be such that fire, once ignited, will continue to spread. Weather is the state of the atmosphere surrounding the earth and its changing nature (Schroeder and Buck 1970). Fire weather is concerned with weather variations within the first 8 km to 16 km (5 mi to 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 temperatures rise, less heat is required. Fire effects such as scorch height are also affected by air temperature. 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. As temperature or pressure rise, 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.

Atmospheric stability. 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 difference 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. 5.x). These winds can cause erratic and severe fire behavior. Ironically, unstable air provides the best conditions for disbursing 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.

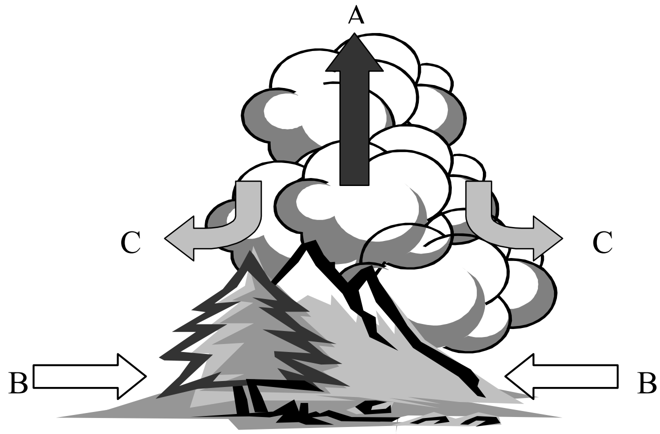


Figure 5.x. *Under conditions of atmospheric instability, heat from the fire rises to form an updraft (A), causing an indraft of air near the surface (B). As the column collapses, strong down draft winds can blow the fire in several directions (C).*

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. Up canyon winds in the morning and down canyon winds in the evening are the result of differential heating and cooling of terrain surfaces (Fig. 5.x). Fire spread is enhanced by transferring heat by convection and by bending the flames closer to the fuel. Embers from torching trees are carried by the wind, starting spot fires ahead of the main fire and increasing its rate of growth.

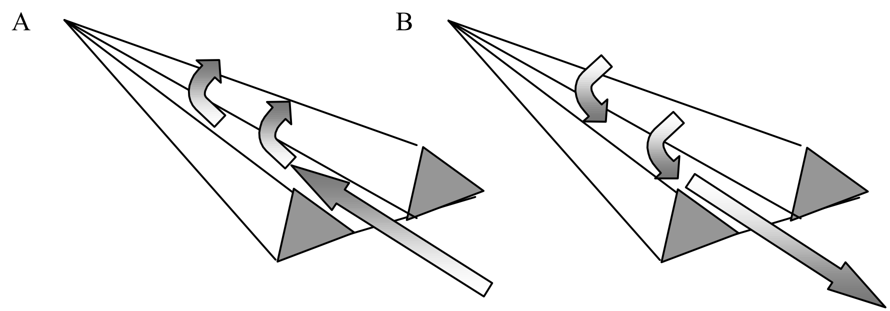


Figure 5.x. *Up canyon and up slope winds occur in the morning as slopes begin to heat and air rises (A). In the evening, winds reverse as slopes cool and air subsides. (From Agee 1993)*

Clouds and Precipitation. Clouds and precipitation affect fire behavior primarily through their effect 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.

Fuels

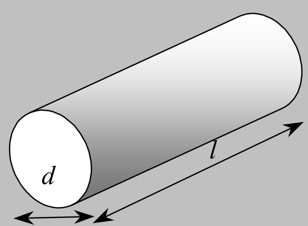
Fuel is the source of heat that sustains the combustion process. Under constant weather and topographic conditions, the characteristics of the fuels determine the rate of combustion. For example, a fire burning in dry grass fuels on a 20 percent slope with a 8 km h^{-1} (5 mi h^{-1}) wind would have a higher rate of spread and be more intense than a fire burning in an equal amount of large woody debris under identical conditions. Similarly, a tall brush field would burn more intensely than 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 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. This would not work because you would not be able to raise the temperature of the log 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 5.1). The smaller the size of a fuel particle, the larger is the ratio between the 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 four (Rothermel and Burgan 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 two. 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.

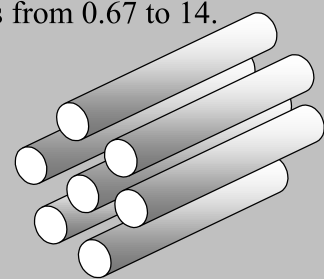
Box 5.1. Surface Area to Volume Ratio. This ratio is calculated by dividing the surface area of a fuel particle by its volume. If you ignore the ends, the equation is simplified to dividing 4 by the diameter of the particle. The ratio is increased if you split the fuels into smaller parts. For example, when a log with a diameter of 6, when split into 7 pieces, the ratio increases from 0.67 to 14.

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

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



$$\text{if } d = 6, \quad SV = 0.67$$



$$\text{if } d = 2, \quad SV = 2, \quad \text{and } 7 \times 2 = 14$$

Fuel moisture content. The amount of moisture that a fuel particle contains is a primary determinant of fire behavior. The interaction of a fuel particle with the ambient moisture regime is dependent o its size. 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 percent of its equilibrium moisture content at a given temperature and relative humidity Lancaster 1970). Table 5.1 shows the various timelag classes and the corresponding woody size classes and duff depth classes.

Timelag Class	Time Period	Woody Fuel Size Class		Duff Fuel Depth Class	
		…..cm…..	…..in…..	…..cm…..	…..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	1.91-10.16	0.75-4.00
1000-hour	Seasonally	7.62-22.86	3.00-9.00	10.16+	4.00+

Table 5.1. Moisture timelag classes and corresponding woody fuel size and duff fuel 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. Moisture trends spanning from several days to weeks are captured by the 100-hour fuels, while 1000-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 of the kindling you just split into a tight bundle and trying to light the bundle. Remembering all the campfires you have lit, you would instead arrange the kindling in a small log cabin or teepee. The volume of wood has not changed, but the amount of air in the fuel bed has increased (Fig. 5.x). 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 (Rothermel and Burgan 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 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.

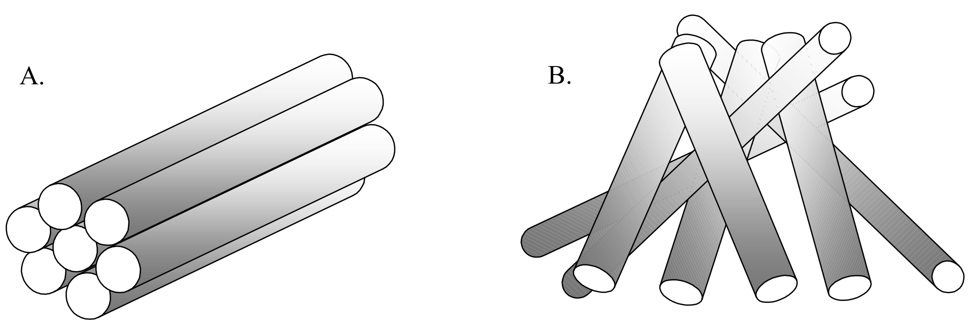


Figure 5.x. *The packing ratio is the proportion of fuel in a unit volume of fuelbed. The same amount of fuel can be packed tightly with only 10 percent air (A) or loosely with 90 percent air (B).*

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 higher the reaction intensity. Rate of spread may actually decrease as load increases; however, the extra fuel 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.

Topography

Elevation.

Slope.

Aspect.

Topographic position.

Fire behavior

Finally, we have the necessary ingredients for a fire: sufficient fuel, conducive weather, and an ignition. We will now look at how these factors, combined with topography, cause a fire to spread. Fires can spread through the surface fuels such as downed woody fuels or shrubs, through the crowns including overstory and understory canopies, or by spot fires ignited by lofted firebrands. Each method has unique physical mechanisms necessary to sustain fire spread. The fuel layer that is burned and the method of spread define fire types. Ground fires burn the duff or other organic matter such as peat and usually burn with slow moving smoldering fires. Surface fires burn the litter and low vegetation fuels with and active flaming front. Passive crown fires burn only single trees, active crown fires burn in the canopies in conjunction with a surface fire, and independent crown fires spread though the canopies without a surface fire.

Flaming front. Characteristics of the flaming front include the forward rate of spread, the flaming zone depth, and the residence time (figure 5.x). Rate of spread is measured in units of distance per unit of time (m min^{-1} or ft min^{-1}) and 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 multiplying the diameter of the particles that were being burned by eight could approximate the residence time in minutes.

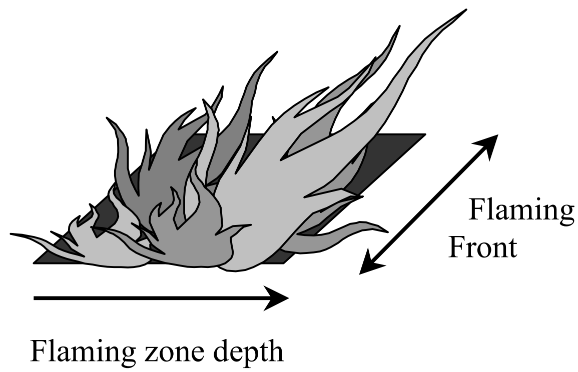


Figure 5.x. *The flaming zone includes the area between the front and back of the flames. The residence time is the time it takes the front of the flame to pass the distance of the flaming zone depth.*

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 and is measured in units of kJ m^{-2} min^{-1} (Btu ft^{-2} min^{-1}). The reaction intensity is the source of heat that keeps the chain reaction of combustion in motion. Fireline intensity is the rate of energy release per unit length of fire front. It is equivalent to the product of the available energy (in terms of heat per unit of area) and the forward rate of spread divided by 60 (the number of seconds in a minute). It can also be determined from reaction intensity and flaming zone depth.

Fireline intensity is likened to the amount of heat you would be exposed to per second while standing immediately in front of the fire. Fireline intensity is related to flame length, the average distance from the base of the flame to its highest point (Fig. 5.x).

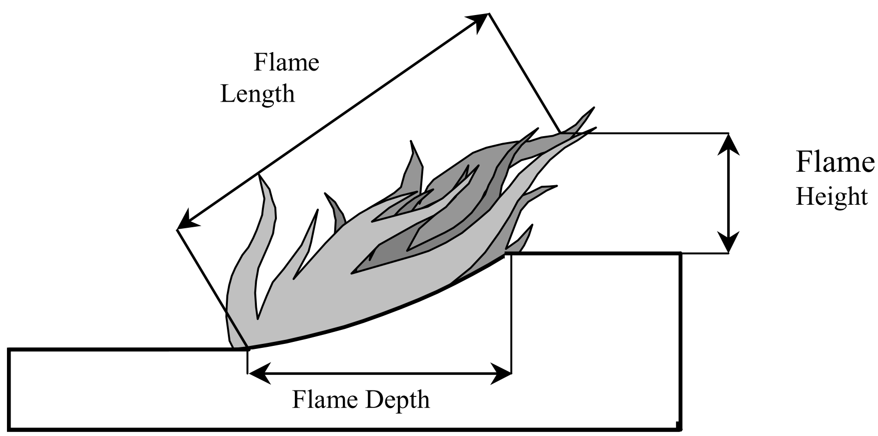


Figure 5.x. *Flame dimensions for a wind driven fire.*

Byram (1959) provided the approximate relationship between fireline intensity and flame length:

$$\text{Flame Length} = 0.237 \times (\text{Fireline Intensity})^{0.46},$$

with the length in m and intensity in kW m^{-1}, or:

$$\text{Flame Length} = 0.45 \times (\text{Fireline Intensity})^{0.46},$$

with the length in ft and the intensity in Btu ft^{-1} s^{-1}.

These equations can be reversed to obtain simple expressions for fireline intensity in terms of flame length. 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 (kJ m^{-2} or Btu ft^{-2}). The heat released per unit of area can be calculated by dividing 60 times the fireline intensity by the rate of spread. The number 60 is used to correct units since intensity uses seconds and rate of spread uses minutes.

Surface fire spread. The first attempt to describe fire spread using a mathematical model was by Fons (1946). He theorized that since sufficient heat is needed at the fire front to ignite adjacent fuels, fire spread could be described as 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, while the unit currently burning is the heat source.

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. Enough 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 Fig. 5.x).

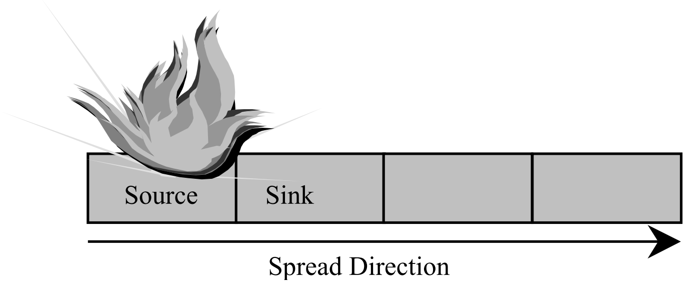


Figure 5.x. *Rate of spread is the ratio between the heat source and the heat sink. As more heat is generated by the source, the more quickly the heat sink ignites*

Since some of the terms in Frandsen's (1971) model contained unknown heat transfer mechanisms. Rothermel (1972) devised experimental and analytical methods to determine the new terms using quantifiable fuel, weather, and topographic variables. His equation was a ratio between the heat source and the heat sink. In the numerator, the heat source was 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, while 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. Empirical relationships were used to define the three terms in the denominator. The final formulation provided an approximate solution to the equation (Burgan and Rothermel 1984):

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

where: R is the forward rate spread of the flaming front, measured in m min^{-1} (ft min^{-1}),

I_R is the 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}),

> is the, propagating flux ratio, the proportion of the reaction intensity reaching the adjacent fuel, dimensionless,

N_w is the wind coefficient which accounts for the effect of wind increasing the propagating flux ratio, dimensionless,

N_s is the slope coefficient, a multiplier for the slope effect on the propagating flux ratio, dimensionless,

D_b is the 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}),

, is the effective heating number, the proportion of the fuel that is raised to ignition temperature, dimensionless,

Q_{ig} is the heat of preignition which is the amount of heat necessary to ignite 1 kg (1 lb) of fuel, measured in kJ kg^{-1} (Btu lb^{-1}).

Each of these terms will be examined individually to gain insight into the complex effects of fuels, weather, and topography on surface fire spread. First we will cover the terms in the numerator. Reaction intensity is made up of several factors that relate to the rate of energy release:

$$I_R = \text{' '}\, w_n\, h\, 0_M\ 0_s\,,$$

where ' ’ is the optimum reaction velocity, measured in min^{-1},

w_n is the net fuel loading, in kg m^{-2} (lb ft^{-2}),

h is the low heat content, in kJ kg-1 (Btu lb-1),

0_M is the moisture damping coefficient, dimensionless,

0_S is the mineral damping coefficient, dimensionless.

Reaction velocity 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 ovendry fuel particle density. Albini (1976) specifies a standard value of 51.25 kg m^{-3} (32 lb ft^{-3}) for fuel particle density. Fuelbed and particle densities for Sierra Nevada conifers are available in van Wagtendonk *et al.* (1996, 1998a). 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 is equal to the ovendry fuel loading multiplied by one minus the fuel particle total mineral content (Albini 1976). Since minerals do not contribute to combustion, their weight must be removed from the calculation of reaction velocity. A mineral content value of 5.55 percent is used for all standard fuel models. Mineral content values for conifers that occur in the Sierra Nevada can be found in van Wagtendonk *et al*. (1998b).

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. There is some variation in heat content for fuels of different species. Conifers tend to have higher values than hardwoods because of the presence of resins and higher lignin content. Sclerophyllous shrubs contain oils and waxes in their leaves that also increase their heat content. Albini (1976) uses a standard value of 18.61 MJ kg^{-1} (8,000 Btu lb^{-1}), although values have been determined for some species (van Wagtendonk *et al*. 1998b).

The moisture and mineral damping coefficients 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. The mineral damping coefficient is a function of the silica free ash content, termed the effective mineral content. A value of 1.00 percent 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 is a dimensionless fraction between the no-wind, no-slope propagating flux and the reaction intensity (Fig. 5.x). The minimum value for the flux ratio is zero when no heat reaches adjacent fuels, and the maximum value is one when all the heat reaches adjacent fuels. These values are seldom seen and a more practical range would be from 0.01 to 0.20. The surface area to volume ratio and 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.

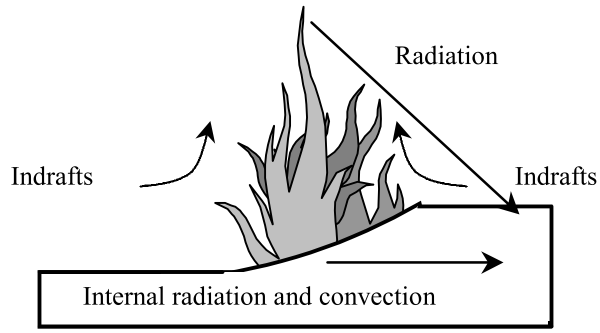


Figure 5.x. *Under no-wind, no-slope conditions, heat is transferred by radiation from the flame and by internal radiation and convection. Indrafts move air up into the flame.*

Both the wind coefficient and slope coefficient 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 windspeed 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 5.x). 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 windspeed. Finer fuels have more surface area exposed to the increased radiation, and this effect becomes greater as windspeed increases. This 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 windspeed beyond which the wind coefficient does not increase (Burgan and Rothermel 1984). At that point the power of the wind forces exceed the convective forces. This occurs when the windspeed in km h^{-1} is twice the reaction intensity in kJ min^{-1} m^{-2} (or the windspeed in mi h^{-1} is 1/100 of the reaction intensity in Btu ft^{-2} min^{-1}).

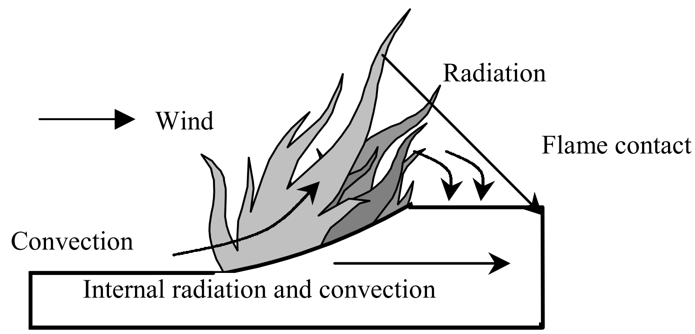


Figure 5.x. *Under no-slope conditions, wind bends the flame closer to the adjacent fuel resulting in increased radiation, convective heat, and flame contact.*

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, there is only a small increase in convection (Fig. 5.x). Standing above a fire on a slope is much hotter than 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.

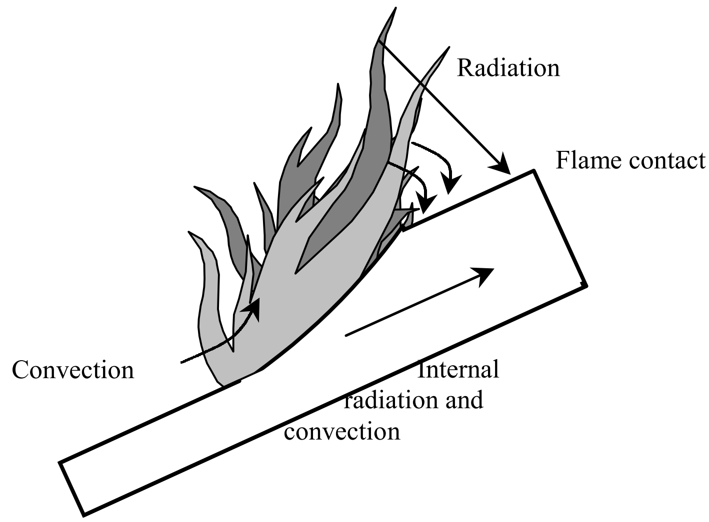


Figure 5.x. *Under no-wind conditions with a slope, the convection component is not as pronounced as it would be with wind. Radiation and flame contact are still important factors for increasing spread.*

Now we will take a look at the terms in the denominator of the surface spread equation that constitute the heat sink. The denominator represents the amount of fuel that needs to be brought up to ignition temperature. The first term is fuelbed bulk density, the total amount of fuel that is potentially available. It is defined as the ovendry weight of the fuel per unit of fuelbed volume and is calculated by dividing the ovendry fuelbed load by the fuelbed depth. Since 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 defines that proportion and is dependent on fuel particle size as measured by the surface area to volume ratio. Small particles will heat completely through and ignite, while decreasing proportions of larger particles will ignite as size increases. Not only do the thinner particles heat all the way through, but their increased surface area also allows the 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 preignition quantifies the amount of heat necessary to raise the temperature of a 1 kg (1 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 preignition. The units are in kJ kg^{-1} (Btu lb^{-1}). The product of the fuelbed bulk density, effective heating number, and the heat of preignition is the heat per unit of area in kg 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 to the canopies of trees. Van Wagner (1977) defined three stages of crown fire. The first stage of crowning is the passive crown fire that begins with the torching of trees. If the fire spreads through the crowns in conjunction with the surface fire, it is called an active crown fire. An independent crown fire spreads through the crowns far ahead of or in the absence of the surface fire.

In a passive crown fire, groups of trees torch out and there might be some intermittent crowning (Fig. 5.x). Torching can occur at low wind speeds with relatively low crown bulk densities and relatively high crown bases. 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 if the flame length is equal to or greater than the height to the crowns or if the surface fire intensity is great enough to bring the crowns to ignition temperature.

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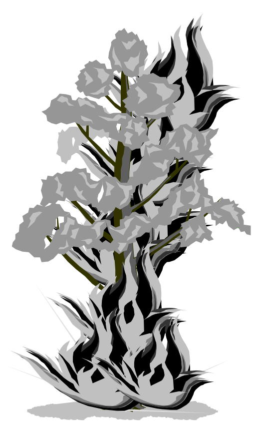

Figure 5.x. *Passive crown fires can occur under conditions of relatively low windspeeds, low crown bulk densities, and high crown bases.*

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). The transition threshold 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).

An active crown fire can result 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 them. The fire becomes a solid wall of flame from the surface to the crown and spreads much faster than the surface fire (Scott 1999). Lower crown base heights and higher wind speeds and crown bulk densities than those necessary for passive crowning are conducive to active crowning (Fig. 5.x). 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 above, 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 kg m^{-3} to 0.05 kg m^{-3} (0.01 lb ft^{-3} to 0.03 lb ft^{-3}). Consequently, the actual spread rate necessary to initiate crown spread is 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 fuels are derived from the crown fraction burned, the mean canopy height, 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).

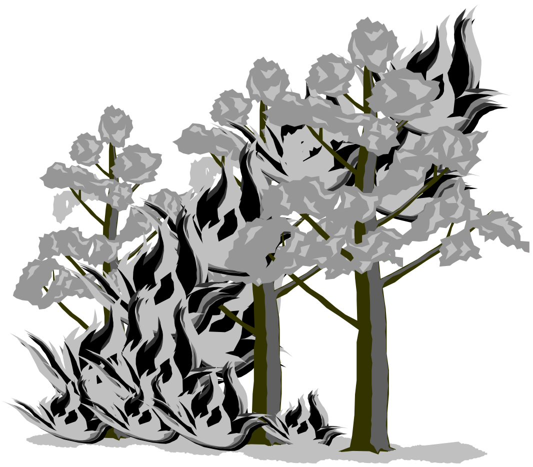

Figure 5.x. *Higher windspeeds and crown bulk densities and lower crown bases lead to active crown fires.*

Independent crown fires burn in aerial fuels substantially ahead of the surface fire and are rare, short-lived phenomena. There is little evidence that these fires occurred over extensive areas during the past several centuries (Swetnam 1993). Very high wind speeds and bulk densities greater than 0.05 kg m^{-3} (0.03 lb ft^{-3}) lend themselves to this extreme behavior of these wind-driven fires (Fig. 5.x). 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.

Figure 5.x. *Very high windspeeds and crown bulk densities can lead to independent crown fires that race ahead of the surface fire.*

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 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 (Wilson 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).

Fire in the context of ecological theory

Succession theory

Ecosystem theory

Disturbance theory

(the only place I will even mention the word)

Hierarchical theory

Effects of fire on Sierra Nevada forests

Patterns of tree mortality

Differential tree 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. If too much of the cambium or canopy is killed, the plant cannot survive. Ryan *et al.* (1988) studied long-term fire-caused mortality of 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 scorch height. Van Wagtendonk (1983) found that flame length was the best predictor of understory mortality of Sierra Nevada conifers. He derived fifty percent mortality curves for ponderosa pine (*Pinus ponderosa*), incense-cedar (*Calocedrus decurrens*), sugar pine (*Pinus lambertiana*), and white fir (*Abies concolor*) for tree height and flame length. Peterson and Ryan (1986) used bark thickness, 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.

Changes in size structure

Changes in spatial pattern

Changes in tree growth rates

Changes in the tree reproduction environment

Seed release

Seed bed. 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 during the smoldering phase of combustion, 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 two 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.

Gaps and competition. 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

Figure 5.x. *Solar radiation and windspeeds are increased and relative humidity is decreased after a fire has opened up a stand.*

temperature at the surface and decrease relative humidity and fuel moisture (Fig. 5.x). 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.

Fire intensity and the degree of exposure of mineral soil govern the response of soils to fire (Wells *et al*. 1979). Fires consume the organic content of soils, volatilize some elements, transform some elements to soluble form, and change the physical, biological, and chemical soil characteristics. Excessive heat can adversely affect land productivity and soil stability by volatilizing excessive amounts of nitrogen and disrupting soil structure. On the other hand, low intensity fires can facilitate recycling of some nutrients and only negligibly affect soil erosion (Wells *et al*. 1979).

Nitrogen fixers

Natural fire regimes

Frequency

Predictability

Magnitude

Extent

Season

Twentieth Century fire regimes

Ignitions
Fuels
Fire behavior
Fire effects

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