2

Fire and fire ecology: Concepts and principles

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2.1 FIRE AND COMBUSTION

Fire has been central to terrestrial life ever since early anaerobic microorganisms poisoned the atmosphere with oxygen and multicellular plant life moved onto land. The combination of fuels, oxygen, and heat gave birth to fire on Earth. Fire is not just another evolutionary challenge that life needed to overcome, it is, in fact, a core ecological process across much of the planet.

What we call fire is a particular form of combustion. Combustion is an oxidation process. Oxidation can happen slowly, at low temperatures, allowing controlled energy release such as occurs during respiration inside living cells. Conversely, it can happen much more rapidly and at substantially higher temperatures during fires. While the intermediate steps vary between the two oxidation processes, the end products are the same: CO_2 and water are released, along with stored energy in the form of sensible heat and light. The rapid oxidation process we call fire is the subject of this chapter.

What is fire? This question has generated much philosophical debate over the millennia but from a mechanistic perspective it is simply the heat and light generated by flaming combustion. Fire begins with combustion, which requires the mixture of heat, fuel, and oxygen in the right proportions (Figure 2.1). In the case of wildland fire, fuels are primarily carbohydrates (cellulose and hemicellulose) derived from vegetative biomass (e.g., foliage, wood, humus, etc.). The combustion process is simply the breaking and reforming of chemical bonds such that the total energy in the rearranged bonds forming the end products is less than the energy in the bonds of the original reactants. The net change in energy embodied by these chemical bond rearrangements is released as heat and light:

$$(C_6H_{12}O_6)_n \longrightarrow 6nCO_2 + 6nH_2O + \text{energy} \tag{2.1}$$

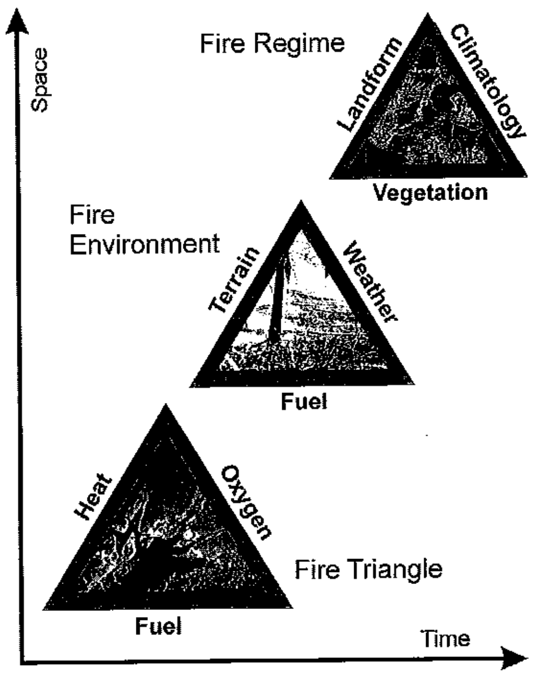

Figure 2.1. Fire concepts change across spatial and temporal scales. At the finest scale (combustion-scale fire triangle), individual fuel beds ignite, burn, and transfer energy to their surroundings. Combustion events range on the scale of several seconds to a couple of days at this microsite scale, and their effects are monitored at the quadrat scale. The fire environment is the summation of all the combustion environments within an individual fire. At this scale, fire behavior monitoring and modeling are used to evaluate fire as fuels, heat, and oxygen vary with terrain and weather within individual fires. Temporal variations of individual fires range from hours to days, weeks, or months as fires spread across landscape-scale land areas. Their effects are assessed by stand-level and community-level surveys. At the highest spatial and temporal scales, fire regime concepts describe the modal fire type that occurs at stand/community, landscape, and biome levels across decadal to century-long time scales. At these scales broad-class descriptors of impacts on major processes are inferred from dendroecological and paleoecological techniques. *See also* Color section.

If the heat transfer is sufficient to continuously oxidize proximate fuels then sustained combustion occurs. When the process volatizes fuels and creates a mass of incandescent gas it is called flaming combustion. Otherwise, if combustion occurs only at the surface of the fuels and without flames, the process is termed smoldering combustion. From an ecosystem perspective, the combustion equation above is essentially photosynthesis being run in reverse, although the steps and interim products involved in the reactions are not completely analogous unless the process occurs within a cell. Outside of a cell, the end result of combustion is that stored energy from sunlight (photons) contained in fuels (biomass) is rapidly released as heat and light.

Rapidly burning organic substances pass through three main phases of combustion: preheating, gaseous, and smoldering. Preheating is the preignition and dehydration phase of the combustion process. This is an endothermic process wherein fuel temperatures are raised, water and other volatiles are evaporated, and combustible gases are distilled from the fuels. Thermal breakdown of organic materials into volatile gases is called pyrolysis. Ignition temperatures for vegetative biomass are about 350°C but cannot be reached until water in the fuels is driven out (Williams, 1982; Saito, 2001; Ward, 2001). Heating water requires 4.18 J/g °C but the heat of vaporization is much greater at 2,290 J/g. Water changes from liquid to vapor phase at 100°C and, until dehydration occurs, a fuel's temperature will not rise above this temperature. In nature, fuel moistures can range from less than 10% to greater than 300% of a fuel's dry weight (Pompe and Vines, 1966; Schroeder and Buck, 1970; Viney, 1991; Pyne *et al.*, 1996; Nelson, 2001). To a large degree, the water content of a fuel determines its flammability. If a fire or other ignition source cannot impart enough energy to dehydrate the fuels then ignition cannot occur. The preheating phase includes everything prior to actual ignition of the fire.

Gaseous combustion is what most people refer to as fire. The gaseous phase of combustion begins when pyrolyzed fuels reach their heat of ignition. This is the temperature to which a fuel, in the presence of air, must be heated to start self-sustained combustion, wherein heat release is sufficient to maintain continued pyrolysis of the proximate solid fuels. Flaming combustion is the rapid oxidation of the volatile gases produced by pyrolysis. These gases must be mixed with oxygen to allow combustion to proceed. For this reason, alterations of airflow due to wind and the packing or arrangement of fuels strongly influence flaming combustion (see Figure 2.2). Pyrolyzed particulates, heated to the point of incandescence, give flames their characteristic colors with the progression from red and orange to yellow and blue denoting cooler to higher temperature flames (Saito, 2001). Particulates that do not achieve complete combustion, and cool below the point of visible incandescence, form the smoke given off by a fire. The temperature at the tip of the visible flame varies somewhat with burning and lighting conditions but is nominally around 500°C (Heskestad, 1997).

The smoldering phase of combustion occurs either when there is insufficient oxygen to support flaming combustion (e.g., in densely packed fuels) or when the easily pyrolyzed substances (volatiles) have been reduced to a level where flaming combustion is no longer possible. This phase includes the progression from the glowing charred zone of fuels to residual char and ash and the eventual extinction of the fire. Smoldering fires spread very slowly along the surfaces of fuels. This allows them a long time in which to transfer heat to the surrounding soil and vegetation. Therefore, although smoldering combustion may not be as hot or release heat as quickly as flaming combustion, it can locally be very destructive. Additionally, smoldering combustion releases very different types and amounts of volatiles and particulates than flaming combustion. Smoldering fires represent less efficient combustion processes and, hence, release more smoke and greater amounts of respirable particulates (e.g., particulates less than 2.5 microns in size) (Ward, 2001; Christian *et al.*, 2003; Urbansky *et al.*, 2009).

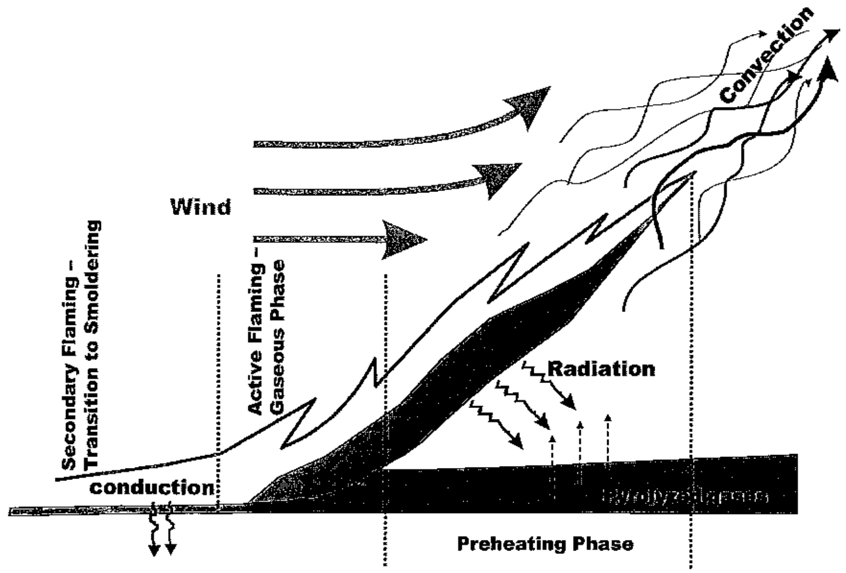

Figure 2.2. Illustration of heat transfer processes in a wildfire. Conduction of heat from molecule to molecule is the primary mode of heat transfer early in the ignition phase of any fire and during smoldering combustion. It is also the way in which heat is transferred into the soil, and characterizes ground fires. Radiation is the primary form of heat transfer for actively spreading flames. Fuels in front of the fire are heated to the point that flammable gases are emitted (pyrolyzation), thereby supporting continued flaming combustion. Convection is the primary manner of heat transport upward to the canopy. Heated atmosphere and the mix of emitted gases expand and rise, causing cooler air to rush in at the base of the fire. *See also* Color section.

2.2 HEAT TRANSFER

A spreading fire is a continuing process of the three phases of combustion, with fuels being preheated to the point of ignition, achieving gaseous and then smoldering combustion before eventually going out (extinction). Therefore, for fires to spread, it is always necessary to transfer adequate amounts of heat to proximate fuels. Heat transfer can be accomplished in three ways: conduction, convection, and radiation. In addition to the three primary heat transfer mechanisms, mass transport of heat, in the form of burning embers, also occurs in wildland fires. If such embers land on suitably dry fuels prior to cessation of their combustion they can ignite new fires, referred to as "spot" fires (Albini, 1983).

2.2.1 Conduction

Conduction is the direct transfer of heat energy from one molecule to another. This is the primary manner of heat transfer at the very beginning of a fire as ignition occurs. It is also important during smoldering combustion. The thermal characteristics of wood are affected by density in two ways. First, higher density wood conducts heat

better, thereby keeping surface temperatures lower as heat is transferred toward cooler portions of the potential fuel. Second, higher density fuels have higher heat capacities than lighter fuels, meaning that greater amounts of heat are necessary to raise their temperatures to the point of ignition. Solid wood is relatively dense and hard to ignite because it quickly conducts heat from its surface to the interior, making the surface heat more slowly. Conversely, rotten wood is less dense, conducts poorly, and is, therefore, easily ignited because surface temperatures rise rapidly under the same heating conditions. However, the ability of these fuels to rapidly take up water may also make them wetter than the adjacent sound fuels, making fire spread difficult or impossible even if ignition at the surface does occur (see Section 2.3.3).

2.2.2 Convection

Convection is the transfer of heat through moving fluids. In the case of fire, the fluid is the atmosphere being heated by the fire. Heated air expands and rises due to its reduced density, carrying heat with it. Convection is the primary method of vertical heat transfer and can preheat tree canopies well above a fire. Convection currents also result in cooler air rushing in at the base of a fire to replace the rising air mass. Under extreme fire conditions, convective winds can become very strong and determine wildfire behavior. Convection is also the mechanism that supplies the inertia for transporting embers up into the atmosphere, potentially igniting additional fires well away from the original fire.

2.2.3 Radiation

Radiation is the main form of heat transfer responsible for preheating fuels. It controls fire spread rates for most wildland fires. Just like the sun, fire emits electromagnetic (EM) waves, although primarily in the visible and near-infrared spectrum. EM radiation does not require a medium for travel and projects in straight lines. The energy flux per unit area drops with distance from the heat source at a rate equal to the inverse of the distance squared. Therefore, at twice the distance, the energy per unit area will be one-fourth as large. This fact is important for understanding how fires propagate. Both the distance and the relative geometry between the various flaming particles and the fuels in the direction of the fire spread (Figure 2.3) determine the amount of heat transferred over time (Rothermel, 1972; Williams, 1982; Sullivan *et al.*, 2003). Because EM waves travel in straight lines, heat transfer is greatest when fuels are perpendicular to the radiating energy. No radiation will reach any fuels protected from exposure to the direct view of the flames. For these reasons, the rate of heat transfer to proximate fuels is much greater for fires moving upslope or in the direction of the wind than for fires moving downslope or into the wind. The greater heat transfer rates for flames angled towards proximate fuels (e.g., upslope or with the wind) raise fuel temperatures to their ignition point more rapidly and result in faster spreading fires or fires that can spread in wetter fuels. Conversely, fires moving downslope or into the wind spread more slowly, if at all, because of the

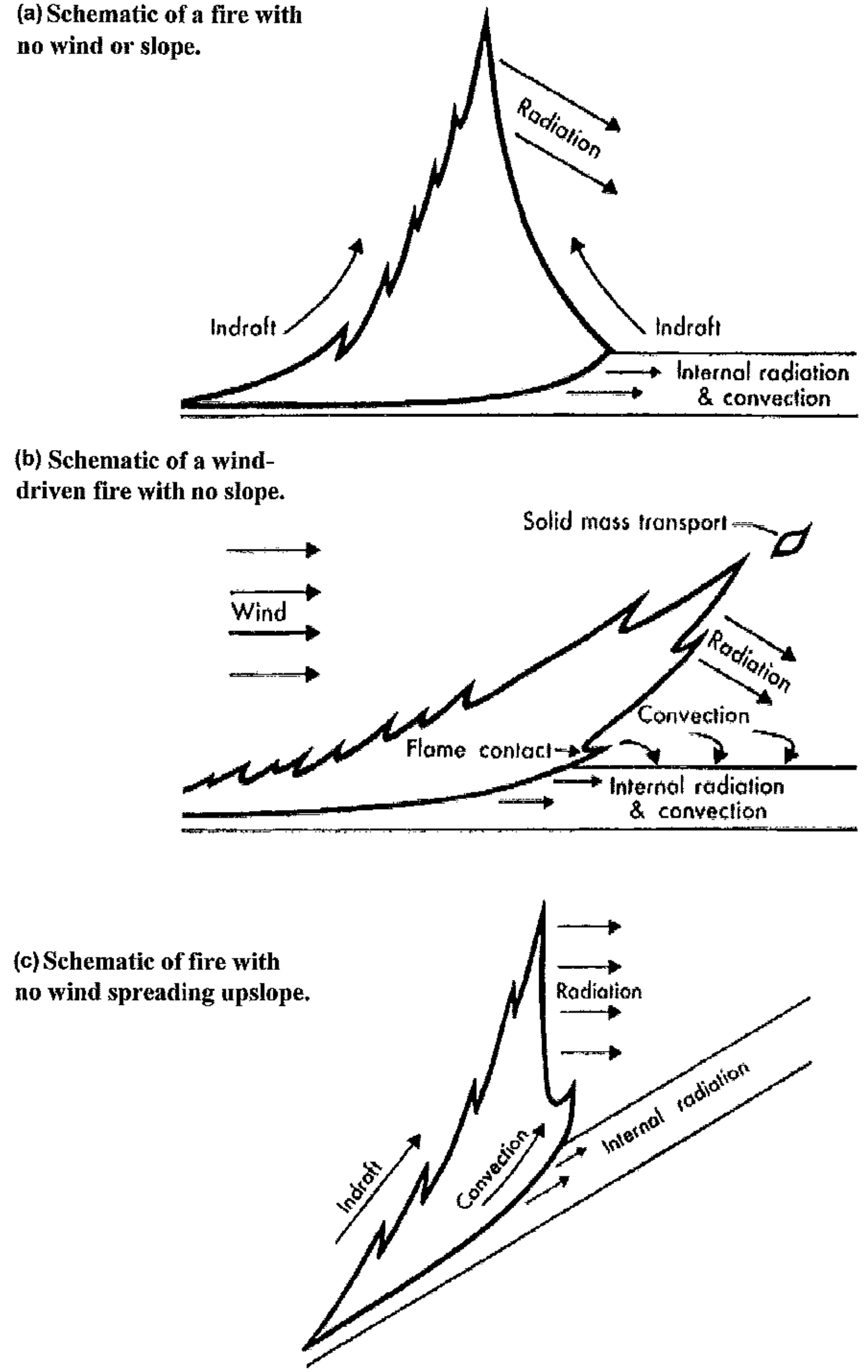

Figure 2.3. Schematic representations of fire spread and relative flame geometry for conditions with and without wind or slope (Rothermel, 1972).

greater distances and less direct angles of incidence between the radiated heat and fuel surfaces.

2.3 FUELS

Photosynthesis is the process whereby living organisms (primarily plants) convert sunlight into chemical energy. In the process, carbon dioxide (CO_2) and water are transformed into atmospheric oxygen (O_2) and carbohydrates. In terms of the end products, the photosynthesis process is effectively the combustion process (Equation 2.1) run in reverse. Plants store energy from sunlight as biomass, and biomass is literally what fuels wildfires. Combustion merely releases this stored energy in the forms of heat and light.

While fuels are any combustible substance, there are many factors related to fuels in wildland systems that govern whether and how fires can burn. Fuel composition, fuel loading and arrangement, fuel moisture, and fuel continuity are all key determinants of wildfire behavior, spreading capacity, and total fuel consumption.

2.3.1 Fuel composition

The relative composition of the constituents of a fuel determines its energy content. Wood is the major form of biomass in forested ecosystems and is primarily comprised of cellulose (41–53%), hemicellulose (15–25%), and lignin (16–33%) (Pyne *et al.*, 1996). Lignin provides added stiffness in woody plants. Grasses and other non-woody ecosystem fuels are dominated by cellulose and hemicellulose, with a smaller lignin component. Lignin is more energetic for combustion than cellulose or hemicellulose and is also resistant to decay by microorganisms. Therefore, as woody materials decay, the relative proportion of lignin in the remaining biomass increases, potentially becoming as high as 65% (Pyne *et al.*, 1996; Ward, 2001). Volatile oils, resins, and other chemical compounds (e.g., aliphatic and aromatic hydrocarbons, alcohols, aldehydes, gums, sugars, terpenes, fats, waxes, and oils) are relatively small but important components of the fuels formed by some plants (Stott, 2000). These substances have very high–energy contents and can easily burn. Conversely, some plants have higher mineral contents that make them relatively retardant to flames (Broido and Nelson, 1964; Philpot, 1970; Mutch and Philpot, 1970; Armstrong and Vines, 1973). At present, fuel composition, chemistry, and the burning characteristics of most tropical ecosystems are poorly known, if at all (Cochrane, 2003).

2.3.2 Fuel loading and arrangement

Fuels include living and dead components of the ecosystem above, at, and below the soil surface. Wildland fuels include leaves, litter, branches, boles, and roots as well as duff, peat, and other forms of soil carbon. Fuel loading refers to the weight of all fuels present per unit area of a site. While this is an important parameter, alone it is of little use in predicting how or if a site will burn. It is important to know how the fuels are distributed by type (live or dead), size distribution, orientation (standing or fallen), heat content (volatile vs. non-volatile), condition (sound or rotten) and spatial arrangement to understand how, or if, the fuels will burn.

Estimation of live fuel loading requires knowledge of the composition and structure of the site and reliance on allometric equations or other proxies for extrapolation of biomass and average wood density. Such information is very limited in tropical ecosystems. Downed woody debris and other surface fuel loads can be estimated in several ways. One of the easiest is the planar intercept method (Brown 1971, 1974). In this method, a hypothetical vertical plane is imagined to cut through an area and the numbers of fuels of different standard size classes are counted. Large fuels are measured directly and noted for condition (sound or rotten). Fuel bed depth is used to determine how tightly the fuels are packed, since this will affect both the availability of oxygen and the amount of heat transferred to the surrounding fuels. The packing ratio is simply the fuel volume divided by bed volume (i.e., the fraction of the volume that is fuel). In addition, the depth of the leaf litter layer is measured. From these data and some knowledge of the average density of the local fuels, it is possible to calculate the amount of surface fuels in different size classes. These data are critical for modeling potential fire behavior and the size classes relate to known fuel moisture time lag classes (see Section 2.3.7 and Table 2.1). Adaptations of the planar intercept method in tropical systems have been made by Kauffman *et al.* (1988), Uhl and Kauffman (1990), Guild *et al.*, (1998), and Cochrane *et al.* (1999).

Subsurface fuels can also be important for some tropical ecosystems. Subsurface fuels include dense root mats, duff, and peat formations. The quantity of subsurface fuels can be immense and vastly exceed the amount of surface and aerial fuels in ecosystems such as peat swamp forests (Page *et al.*, 2002, this book). Although these fuels burn only under the driest conditions, subsurface fires (ground fires) can be extremely severe with heavy mortality of vegetation and large amounts of emissions (Hungerford *et al.*, 1995; Bertschi *et al.*, 2003; Reardon *et al.*, 2007).

The sum of all the fuel characteristics of an ecosystem or location describes its fuel complex. Fuel complexes vary tremendously in their physical and chemical properties. Given the current state of knowledge, raw biomass data may be aggregated up to describe numerous attributes of a fuel complex but these cannot be directly used to calculate fire potential owing to the complexities of the combustion and heat transfer processes. In practice, fuel models are developed to describe fuel complexes for given landcover types as an alternative. These fuel models incorporate all of the necessary fuel characteristics for modeling fire spread and flame characteristics, but such descriptions are fire model–dependent (Rothermel, 1972; Finney, 1998; Linn *et al.*, 2005; Sandberg *et al.*, 2007; Andrews and Bevins, 2008). Standard fuel complex descriptions (Anderson, 1982; Scott and Burgan, 2005) have been widely used for fire modeling in temperate ecosystems. However, standard fuel models for most tropical ecosystems are not available, excepting some of the grasslands of Australia (Cheney and Sullivan, 1997), submontane forests and shrublands of Mexico (Alvarado-Celestino *et al.*, 2008), cerrado ecosystems of Brazil (Ottmar *et al.*, 2001) and several Hawaiian ecosystems (Wright *et al.*, 2002; Ottmar *et al.*, 2007).

2.3.3 Fuel moisture

It is not enough to have fuel, oxygen, and a spark to start a fire. As mentioned in the combustion section, fuel moisture is a key determinant of the flammability of a given fuel. If a fire cannot impart enough energy to the surrounding fuels before self-extinguishing then the fire cannot spread. Only fuels that are present and can be consumed by a fire under the existing conditions are considered "available fuels". By definition, available fuels are those fuels which actually burn during a given fire. The concept of fuel availability is a fundamental reason that high-biomass systems such as tropical rainforests can exist while rarely burning. Given their productivity, there is plenty of fuel that could potentially burn. The ubiquitous presence of natural and anthropogenic ignitions (Cochrane, 2003) also means that there are plentiful opportunities for fires to start. High humidity beneath intact forest canopies keeps fuels too moist to burn under all but the most severe drought conditions (Cochrane, this book, a). Fuel moisture is the regulator of fire in these systems (Ryan, 1991).

2.3.4 Total fuels

The total or potential fuel load is the proportion of the total biomass that could burn during a worst-case scenario (Pyne *et al.*, 1996; DeBano *et al.*, 1998). For example, the boles and coarse branch wood of solid, standing green trees cannot burn in an initial fire because the stems are too widely spaced to effectively reinforce combustion. Thus, fires self-extinguish after passage of the flame front (Albini and Reinhardt 1997). Therefore, the total biomass, which is all biomass at a site (potentially exceeding 300 Mg/ha) is not synonymous with the total fuel load. The biomass may primarily be composed of fuels that are not capable of carrying a fire. Thus total biomass $\geq$ total fuel $\geq$ available fuel, and fuel moisture is a major determinant of the inequality in any given ecosystem (Figure 2.4). The critical problem to be solved when predicting fire behavior is to determine which fuels are available. The amount of moisture beyond which fires no longer spread is termed the moisture of extinction (Rothermel, 1972; Albini, 1976; Wilson, 1985).

2.3.5 Live fuels

Live fuels are parts of living vegetation. Live fuel moisture content is the ratio of the amount of moisture to the amount of dry plant material and is largely controlled by internal physiological mechanisms (Nelson, 2001) (Table 2.2).

The moisture content is calculated as:

$$\text{moisture} = \text{moist fuel weight} - \text{dry fuel weight}$$

$$\text{fuel moisture} = \text{moisture}/\text{dry fuel weight}$$

Table 2.1. Surface fuel loads for several tropical ecosystem types and conditions.

Ecosystem	*Fuel quantities*						
	Litter/grass (Mg/ha)	*Root/duff* (Mg/ha)	*1 h* (Mg/ha)	*10 h* (Mg/ha)	*100 h* (Mg/ha)	*1,000 hr* (Mg/ha)	*Total* (Mg/ha)
Bana[1]	2.8 ± 0.3	8.2 ± 0.7	0.22 ± 0.04	0.9 ± 0.2	0.5 ± 0.2	0.0 ± 0.0	13 ± 2
Caatinga	13.2 ± 0.33	5.8 ± 2.7	0.34 ± 0.03	1.0 ± 0.1	1.6 ± 0.6	2.5 ± 1.6	44 ± 3
Second growth[1]	3.8 ± 0.6	17.2 ± 2.4	0.53 ± 0.07	0.8 ± 0.2	0.2 ± 0.2	40.9 ± 18.2	63 ± 15
Species-rich terra firme[1]	2.4 ± 0.14	8.6 ± 1.9	0.61 ± 0.07	1.7 ± 0.4	3.1 ± 1.2	7.6 ± 4.9	64 ± 20
Species-dominant terra firme[1]	3.1 ± 0.3	77.9 ± 8.7	0.48 ± 0.03	1.3 ± 0.2	2.0 ± 0.6	23.1 ± 10.3	107 ± 10
Low igapo[1]	8.0 ± 0.6	231 ± 12.4	0.31 ± 0.03	2.1 ± 0.4	1.5 ± 0.6	10.6 ± 6.4	253 ± 15
Montane subtropical coniferous forest[2]	6.09	10.77	0.25	0.70	3.35	12.37	62.78[b]
Montane subtropical mixed forest[3]	3.93	41.26	0.97	1.81	2.93	7.10	69.22[b]
Cerrado *sensu stricto*[4]	3.4[a]	NA	1.32	3.29	0.46	0.0	8.47
Cerrado denso[5]	5.44[a]	NA	1.63	1.69	4.51	3.95	17.22
Campo sujo[6]	10.28[a]	NA	1.56	0.73	0.76	0.0	13.33
Campo limpo[7]	16.0[a]	NA	0.33	0.24	0.0	0.0	16.57
Coniferous forest[8]	11.01	38.04	0.43	2.24	7.04	89.58	146.09
Broadleaf forest[8]	12.15	NA	0.47	0.96	0.0	0.0	13.58
Grassland[8]	16.63[a]	NA	0.0	0.0	0.0	0.0	16.63
Shrubland[8]	**6.64[a]**	**NA**	**0.09**	**0.61**	**0.0**	**0.0**	**7.33**
Woodland[8]	8.74[a]	NA	2.17	1.35	2.89	0.40	15.56
Tropical deciduous forest[9]	4.7	NA	1.4 ± 0.2	1.1 ± 0.2	3.4 ± 0.3	15.9 ± 1.6	26.2 ± 1.7
Tropical moist forest[9]	5.0	n.a	3.0 ± 0.1	2.1 ± 0.1	7.1 ± 6.9	38.3 ± 12.3	55.4 ± 5.5
Tropical dry thorn forest[9]	0.5	n.a	0.7 ± 0.2	0.6 ± 0.1	1.1 ± 0.8	2.5 ± 0.7	5.4 ± 1.4
Closed-canopy forest condition							
Primary forest[10]	4.1 ± 0.2	n.a	0.9 ± 0.2	2.6 ± 0.6	5.7 ± 2.5	42.3 ± 19.7	55.6 ± 16.2
Logged forest[10]	6.1 ± 0.3	n.a	3.3 ± 0.6	8.7 ± 2.0	23.4 ± 4.5	137.4 ± 42.0	178.8 ± 41.2
Second-growth forest[10]	4.2 ± 0.0	NA	0.9 ± 0.1	2.7 ± 0.5	1.0 ± 3.3	18.8 ± 9.0	27.7 ± 6.7
Unburned forest[11]	3.0 ± 5.0	NA	1.3	5.2	16.8	15.5	42.8
Once-burned forest[11]	3.0 ± 5.0	NA	3.3	11.8	36.8	124.9	180.8
Twice-burned forest[11]	3.0 ± 5.0	NA	6.6	16.9	40.1	106.1	173.7
Slashed primary forest[12]	7.3 ± 0.9	6.9 ± 1.5	4.6 ± 0.7	17.9 ± 2.0	46.9 ± 5.4	75.6 ± 9.2	354.8 ± 47.8[b]
Slashed primary forest[12]	12.4 ± 1.1	3.2 ± 0.8	4.7 ± 0.6	15.6 ± 1.6	59.8 ± 7.9	86.7 ± 10.9	398.8 ± 44.7[b]
Pasture (deforested)[12]	9.5 ± 0.8*	NA	0.1 ± <0.1	0.5 ± 0.2	1.0 ± 0.4	8.1 ± 2.5	66.3 ± 13.3[b]

[1] Amazon Territory, Venezuela (Kauffman *et al.*, 1988). [2] Mexico (N 19 37' 34.16" W 104 18'15.48", 2,095 m) (Alvarado-Celestino *et al.*, 2008). [3] Mexico (N 19°27'12.09", W 103°56'18.57", 2,382 m) (Alvarado-Celestino *et al.*, 2008). [4] Minas Gerais, Brazil (Ottmar *et al.*, 2001). [5] Federal District, Brazil (Ottmar *et al.*, 2001). [6] Brasilia, Brazil (Ottmar *et al.*, 2001). [7] Goiás, Brazil (Ottmar *et al.*, 2001). [8] Hawaii, United States (Wright *et al.*2002). [9] Western Ghats, India (Kodandapani *et al.*, 2009). [10] Paragominas, Pará, Brazil (Uhl and Kauffman, 1990). [11] Tailândia, Pará, Brazil (Cochrane *et al.*, 1999). [12] Jamari, Rondonia, Brazil (Guild *et al.*, 1998).
[a] Includes live and dead grasses.
[b] Includes large trees not included in other fuel classes.
NA = not applicable.

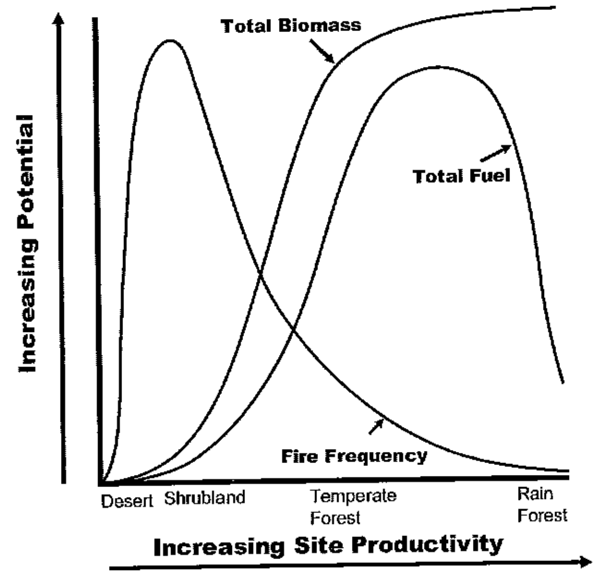

Figure 2.4. Fire frequency, total fuel, and total biomass curves. Fire frequency and potential energy release (E, where E = total fuel mass × fuel heat content) vary with site productivity. In arid and semi-arid environments low biomass productivity results in insufficient fuel to support fire propagation resulting in low fire frequencies. As site productivity increases, greater biomass accumulations occur. These fuels are frequently dry enough to support sustained combustion, resulting in high fire frequency. With increasing moisture availability, biomass productivity increases, resulting in more total fuel existing at a site. However, high fuel moistures reduce the periods of time when fuels are sufficiently dry to support fire spread, leading to a decline in fire frequency. In rainforests high decomposition rates can limit the amount of fine dead fuel at a site, limiting the potential for fire spread, even during extensive droughts. Furthermore, large amounts of biomass are tied up in tree stems which are too widely spaced to support sustained combustion, resulting in low fire frequency (adapted from Ryan, 1991).

Table 2.2. Estimation of live fuel moisture (adapted from Rothermel, 1983).

Stage of vegetative development	*Moisture content* (%)
Fresh foliage, annuals developing, early in growing cycle	300
Maturing foliage, still developing with full turgor	200
Mature foliage, new growth complete and comparable with older perennial foliage	100
Entering dormancy, coloration starting, some leaves may have dropped from stem	50
Completely cured	Less than 30, treat as a dead fuel

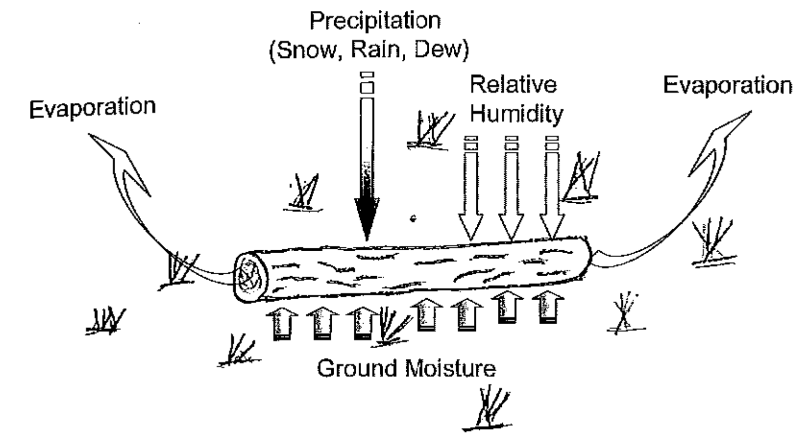

Figure 2.5. Dead fuel moisture of wildland fuels varies with moisture availability, ambient environmental conditions, and time of exposure. Increasing temperatures and wind will augment evaporation rates. Area of ground contact, duration (not intensity) of precipitation events, and exposure to high relative humidity in the atmosphere will increase moisture uptake. Larger diameter fuels dry more slowly than finer fuels but they also take longer to regain moisture from wetter environmental conditions. Across the landscape, fuel moisture levels are a dynamic process of moisture gains and losses that vary by slope, aspect, sun angle (time of day and time of year), and exposure of the fuels (figure adapted from Pyne *et al.*, 1996; drawn by S.M.V. Cochrane).

2.3.6 Dead fuels

Dead fuels, on the other hand, refer to the nonliving remains and detritus from living vegetation. Dead fuel moisture content is calculated similarly (moisture/dry weight) but is largely a function of external weather events (e.g., precipitation), ambient relative humidity, and ground moisture as well as air temperature and exposure to wind and sun. Depending on the relative moisture contents of the fuels and the atmosphere or soils they are in contact with, moisture will either be absorbed by or evaporated from the fuels (Figure 2.5).

2.3.7 Moisture exchange

The rate at which dead fuels exchange moisture with the surrounding environment is related to their surface area, which is generally a function of their diameter. Larger diameter fuels respond more slowly than finer fuels to changes in ambient moisture conditions. This rate of response, or time lag, for different sized fuels refers to the amount of time that the fuel takes to reach 63.2% ($1 - 1/e$) of what would be its new equilibrium moisture content under the changed environmental conditions (Schroeder and Buck, 1970; Agee, 1993). Because environmental conditions are constantly changing, in field practice the time lag is the same whether fuels are gaining (adsorption) or losing (desorption) moisture. In the laboratory, however, time lags vary somewhat depending on whether or not the fuel is in the adsorption or desorption mode (Nelson, 2001). Although the actual time lags of fuels vary continuously over different diameter sizes, they have typically been classed into standard time lag classes. These time lag classes are 1 h, 10 h, 100 h, and 1,000 h which respectfully relate to fuel diameter ranges of 0–0.64 cm, 0.64–2.54 cm, 2.54–7.62 cm, and 7.62–20.32 cm. What the time lag values mean is that smaller fuels, such as 1 h fuels, become drier (desorption) or moister (adsorption) rather quickly compared with larger fuels (e.g., 1,000 h) and organic soils that require extended periods of drought or precipitation to substantially change fuel moisture levels (UNEP, 2002). For open canopy forests, grasslands, and shrublands, fuel moisture is tightly coupled to recent weather conditions and can be estimated across the landscape for any given conditions based on the aspect, slope, elevation, and level of exposure (Rothermel, 1983). Unfortunately, subcanopy temperature, air moisture, and airflow in closed-canopy tropical forests are largely decoupled from local weather conditions, making such estimation of fuel moisture more complicated (Cochrane 2003, this book, a; Messina and Cochrane, 2007) depending on whether or not atmospheric conditions are measured above or below the canopy.

2.3.8 Fuel continuity

For a fire to spread, there have to be fuels that are dry enough to ignite. However, if those fuels are not arranged continuously across the land surface then the fire cannot spread uniformly. Fuel continuity is a necessary component of the environment of a wildland fire. Fuel continuity is defined as the degree or extent of continuous or uninterrupted distributions of fuel particles in a fuel bed. Thus, fuel continuity affects a fire's ability to sustain combustion and spread. This applies to aerial fuels as well as surface fuels. In other words, fuel continuity pertains to the distribution of fuels in both the horizontal and vertical planes. It is necessary to understand that fuel continuity is not an intrinsic property of a landscape. Fuel continuity will vary moment by moment, day by day, and year by year. For example, the optimum packing ratio for fire spread varies with wind speed (Rothermel, 1972). Thus, fuel beds that are discontinuous and will not carry fire at low wind speeds may behave as continuous fuel beds and carry fire at moderate wind speeds. It is commonly observed that fire behavior changes dramatically with modest changes in wind speed (Rothermel, 1972, 1983; Van Wagner, 1977; Cheney and Sullivan, 1997; Finney, 1998; Scott and Reinhardt, 2001). Likewise it is common for fires to spread through discontinuous fuels only at the head, failing to spread on the flanks or to the back due to the reduced intensity (Catchpole *et al.*, 1982a, b; Ryan, 2002). Discontinuities in the fuel extent are fuelbreaks. Fuelbreaks can have clear boundaries, such as when a road crosses an area, or they can be subtle areas wherein the fuel moisture is slightly higher or the packing ratio of the fuels is too high or low to support flaming combustion. However, the efficacies of these fuelbreaks depend on the conditions under which a given fire is spreading. Anything that changes fuel characteristics such that fire behavior is altered can determine if there is sufficient fuel continuity for fire spread. On seasonal to annual scales this might reflect vegetation growth; on daily to

hourly scales it might pertain to changes in fuel moisture; and on smaller time scales it can signify the effects of changes in wind speed or direction.

2.4 OXYGEN

The third component of the proverbial fire triangle is oxygen. Heat and fuel are not enough to create the combustion process. Without sufficient oxygen there will be no fire. At sea level, the atmosphere normally contains 21% oxygen. At 21°C, flaming combustion can continue until oxygen levels fall as low as 14% to 16%. The hotter the environment, the less oxygen is required to maintain flaming combustion. Once started, smoldering combustion can continue at very low oxygen levels. In wildland fires, oxygen is rarely limiting outside of tightly packed fuels (e.g., duff or peat). During intense fires, however, oxygen can become locally depleted, allowing superheating of volatile gases that burst into flames once they expand and mix with oxygenated air. In exposed ecosystems, wind can be the primary factor controlling fire behavior. Wind acts to rapidly aerate the burning fuel bed and can increase both the rate of combustion and the transfer of heat to surrounding fuels by forcing the flames to bend closer to the ground in the direction of fire spread. The net effect of increased wind speed is therefore to create more intense and faster spreading fires. Changes in wind direction can also rapidly change the rate and direction of fire spread. Fuel characteristics determine the potential energy that can be released by a fire, but airflow regulates the rate at which it will be released and therefore influences the amount of fuel that is "available" for combustion.

2.5 WILDLAND FIRE

Wildland fires pertain to all nonstructure fires in regions of limited or no development. These fires can be naturally occurring, intentionally set, or accidental in nature. They can be managed burns or completely uncontrolled wildfires. The modifying forces of topography, fuel, and weather shape fire behavior and comprise the fire environment (Figure 2.1). Wildland fires have both physical and ecological effects. The physical characteristics of fires shape and are shaped by the ecosystems through which they burn (Heinselman, 1981, 1983; Kilgore, 1981; Agee, 1993; Bradstock *et al.*, 2002; Ryan, 2002; Sugihara *et al.*, 2006). In order to understand the direct effects of fires it is necessary to understand how their different characteristics interact with the surrounding environment. However, knowing the physical characteristics of fires is not enough to predict their impact on the affected ecosystems, because the changes wrought by the fires are themselves a function of the temporal and spatial contexts of the events. These interrelated factors are described below.

Table 2.3. Representative ranges for fire behavior characteristics for ground, surface, and crown fi (modified from Ryan, 2002).

Fire type	*Dominant combustion*	*General description*	*Fire behavior characteristics*		
			Rate of spread (m/min)	*Flame length* (m)	*Fireline intensity* (kW/m)
Ground	Smoldering	Creeping	0.00033–0.016	0.0	<10
Surface	Flaming	Creeping Active/Spreading Intense/Running	<0.3 0.3–8.3 8.3–50	0.1–0.5 0.5–1.5 1.5–3.0	1.7–58 58–630 630–2,800
Transition	Flaming	Passive crowning (intermittent torching)	Variable[a]	3.0–10.0	Variable[a]
Crowning	Flaming	Active crowning Independent crowning	15–100 Up to *ca.* 200	5.0–15[b] Up to *ca.* 70[b]	10,000–100,000 Up to *ca.* 2,700,0

[a] Rates of spread, flame length, and fireline intensity vary widely in transitional fires (transitioning between sur and crown fire behavior). In transition fires, surface fires may creep slowly until they encounter branches near ground, causing individual or clumps of trees to torch. Embers lofted from torching vegetation can start additio fires. In contrast, as surface fires become more intense, torching commonly occurs prior to onset of active crownin the fire.

[b] Flame lengths are highly variable in crown fires. They commonly range from 1.5 to 2 times canopy height. F managers frequently report much higher flames but these are difficult to verify or model. Such extreme fires unlikely to result in additional fire effects within a stand but are commonly associated with large patches of contin severe burning.

2.5.1 Fire types

Given that fuels, weather, and terrain typically vary over small spatial or short temporal scales, wildland fires are rarely constant or homogeneous in either their behavior or effects over large areas. Fires can spread along the ground surface, beneath it, or even above it, if the vegetation structure allows. The nomenclature for these fire behaviors are surface fires, ground fires, and crown (aerial) fires, respectively. Individual wildland fires can exhibit any or all of these general fire behaviors (Table 2.3). Each of these fire behaviors is described briefly below.

2.5.1.1 Surface fires

Surface fires burn through loose debris on top of the ground, including such fuels as dead branches, leaves, and low-growing vegetation. These fires can be of either flaming or smoldering combustion. As the spread rate of the latter is typically low (<10 centimeters per hour; Rowe, 1983; Van Wagner, 1983; Frandsen, 1991b; Hungerford *et al.*, 1995) the vast majority of area is burned by flaming combustion. Spread rates and intensity of flaming surface fires are strongly affected by both wind and fuel moisture. Surface fires are most likely to kill trees by damaging their boles near ground level but convected heat may scorch foliage and buds as well.

2.5.1.2 Ground fires

Ground fires consume organic material (e.g., peat, duff, root mats) beneath the level of the surface litter. These fires are generally smoldering combustion and are not much affected by wind or other weather conditions. Ground fires are often started by passing surface fires and can ignite additional or future surface fires as they continue to spread. Ground fires can be extremely difficult to extinguish and may continue for weeks, months, or years. These fires heat and kill the roots of the overlaying vegetation and give off tremendous amounts of particulate emissions (Figure 2.6).

2.5.1.3 Crown fires

Crown or aerial fires advance through the tree or shrub canopy, passing from top to top of each stem. These fires are always flaming combustion and are often started and controlled by an underlying surface fire. Three subtypes of canopy fires are passive, active, and independent crown fires. Passive crown fires are characterized by periodic torching of individual or clumps of trees or shrubs as surface fires pass beneath. Active crown fires spread continuously through the canopy but only in conjunction with the underlying surface fires. This is because they are dependent on the energy from the surface fire to preheat the aerial canopy fuels sufficiently to allow combustion of the moist green vegetation. Independent crown fires are usually active crown fires that begin to spread freely in advance of the surface fire. Independent crown fires spread through the canopy independent of a surface fire. This type of fire requires severe drought conditions including low live fuel moisture and/or strong winds. These fires spread very rapidly but are usually short-lived, dropping back to the surface when conditions do not allow for running crown fires. Crown fires consume the foliage of trees and shrubs, thereby severely damaging or killing them.

2.5.2 Fire characteristics

A fire has several characteristics related to the amount and rate of energy release. This energy release governs the amount of ecological work or net change in ecosystem state (Ryan, 2002) that a fire can accomplish. Energy transfer from the fire to the surrounding environment will determine how an ecosystem will be impacted by and respond to a fire event. Key fire characteristics are flame height, flame length, fireline intensity, spread rate, flame depth, and residence time (Figure 2.7).

2.5.2.1 Flame height

Flame height is the perpendicular distance from the top of the flame to the ground surface. Flame angle is important because it adjusts the distance between the flame and the proximate fuels in the direction of fire spread. The flame angle, measured in degrees, is the angle between the flame at the leading edge of the fire front and the

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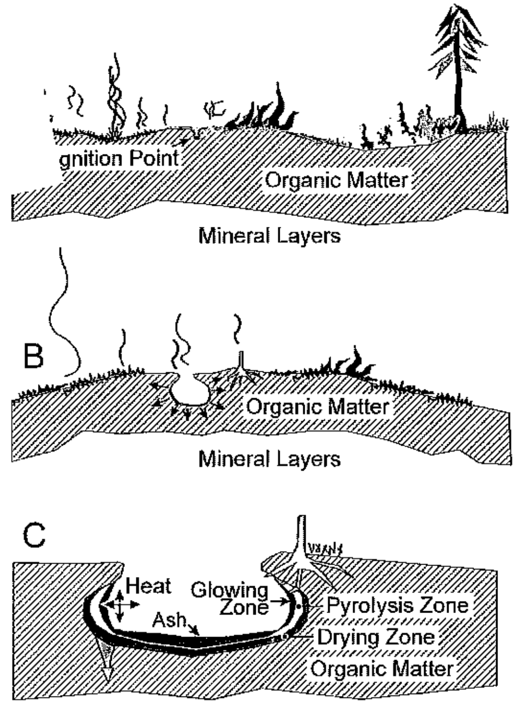

Figure 2.6. Cross-sectional diagram of an organic soil horizon (e.g., duff, peat, muck). Passage of a surface fire (a) ignites more burnable fuels at a number of points on the surface. Under marginal burning conditions (high moisture content), there are few points of ignition and many self-extinguish (Frandsen, 1991a, b). Under drier conditions, there are numerous ignition points. Once established, ignition points develop into combustion fronts (b) that burn both vertically and horizontally. Heat generated by glowing combustion dries and initiates pyrolysis of organic soils in advance of the combustion front (c). The residual ash insulates the combustion zone from excessive heat loss to the atmosphere but also reduces oxygen flow. The process continues until either a moisture limit is reached or all organic soil is consumed.

ground. Flame angles will be <90° when the fire is traveling upslope or with a wind and is termed a head or heading fire. Flame angles will be >90° when the fire is traveling downslope or against a wind and is termed a back or backing fire (Figure 2.7). Spreading fires that are neither heading fires nor backing fires are termed flank fires or flanking fires (Figure 2.8). Fire spread rates will be enhanced for acute flame angles and diminished for obtuse angles.

2.5.2.2 *Flame length and fireline intensity*

Flame length is the distance from the tip of the flame to the midpoint of the flame depth. This is not the same as the height of the flames (see Section 2.5.2.1) unless the

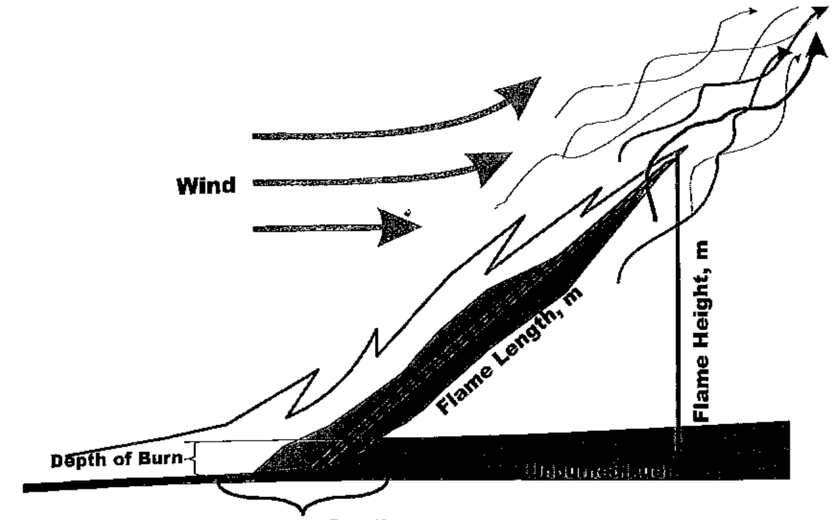

Figure 2.7. Fire anatomy. Three main components used to characterize flaming combustion during a wildland fire are the flame length, height, and depth. The distance from the base of the surface fuels to the flame tip is the flame length. It is proportional to the energy release rate from the fireline (see Section 2.5.2.3) and can be used to estimate the likely height of crown scorch caused by heat convected from the fire (see Section 2.5.2.4). The flame height is the perpendicular distance from the fuel layer to the flame tip. Flame length and height will be equal if there is no wind or slope. Flame depth is the width of the flaming front and is related to the amount of fuel, spread rate, and rate of combustion. *See also* Color section.

fire is occurring on flat ground and in the absence of wind. At all flame angles other than 90°, flame length will be greater than flame height (Figure 2.7).

2.5.2.3 *Fireline intensity*

Flame length is directly related to the intensity (rate of energy release) of the fire. The intensity (I) corresponds to the energy in kilowatts (kW) released by each meter (m) of fireline of a given flame length (F_L). Flame length is expressed in meters (m) and the resultant intensity is given in kW/m (Rothermel and Deeming, 1980):

$$\text{fireline intensity (kW/m): } I = 258F_L^{2.17} \quad (2.2)$$

2.5.2.4 *Height of crown scorch*

Fireline intensity is useful for estimating the height to which foliage will be scorched by passing flames. The convected heat plume can raise foliage temperatures well above the fire to lethal levels. Vegetation with much or all of its foliage below this height may be top-killed by the passing fire. Van Wagner (1973) provided equations for estimating the height of crown scorch (H_s) under various conditions.

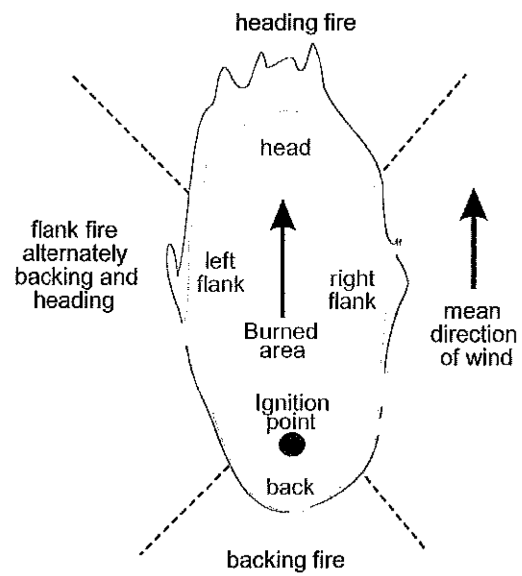

Figure 2.8. Wildland fire spread. Portions of the fire that are moving with the wind and/or upslope are termed head or heading fires. The flames of this section of the fire will tend to be closer to the proximate fuels (flame angles <90°), resulting in more rapid heating, faster pyrolyzation, greater fire intensity, and faster spread rates. Back or backing fires spread against the wind and/or downslope. [Note: Back-fire is also a term used in fire suppression when a fire is set to consume fuels in advance of a spreading wildland fire.] These fires have flame angles >90°, resulting in slower heating of fuels, less pyrolyzation, lower fireline intensities and slower spread rates. Flank or flanking fires are intermediary between heading and backing fires, there may be little or no tilt of the flame (flame angle = 90°) or they may oscillate between heading and backing conditions. Fire spread conditions will change with the topography as the fire spreads across the landscape and may also shift rapidly and dramatically in character with changes in weather conditions and wind directions.

The simplest estimation relates the height of crown scorch (H_s) in meters directly to fireline intensity (I). This equation assumes no wind, a temperature of 25°C, and mortality of foliage and buds at 60°C:

$$H_s = 0.148 I^{2/3} \tag{2.3}$$

While convenient, this equation may not be appropriate throughout much of the tropics due to ambient temperatures that are frequently higher than the assumed temperature for the equation (Figure 2.9). Therefore, the height of crown scorch can be corrected for ambient temperature (T_a):

$$H_s = 4.469 I^{2/3}/(60 - T_a) \tag{2.4}$$

Similarly, the height of crown scorch can be corrected for both temperature and wind, where U is the wind speed in meters per second (m/s):

$$H_s = 0.741 I^{7/6}/(0.0256 I + U^3)^{1/2}(60 - T_a) \tag{2.5}$$

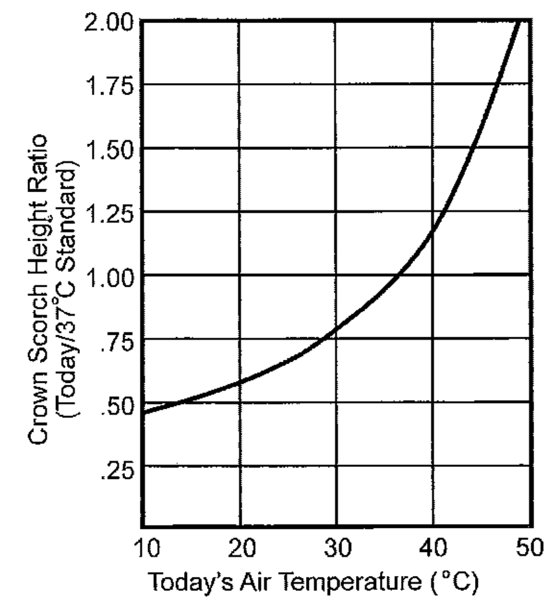

Figure 2.9. Relative height of crown scorch as a function of ambient temperature. In the graph, 37°C is set as the standard, and the y-axis shows the ratio of crown scorch heights for different ambient temperatures with all other conditions held equal.

Although increasing wind speeds will tend to increase fireline intensity, for a given intensity, larger wind speeds will tilt the convection plume and reduce the height of crown scorch (Figure 2.10). Note, however, that both of the corrected equations are based on graphical curve fitting done by Van Wagner (1973) and do not exactly

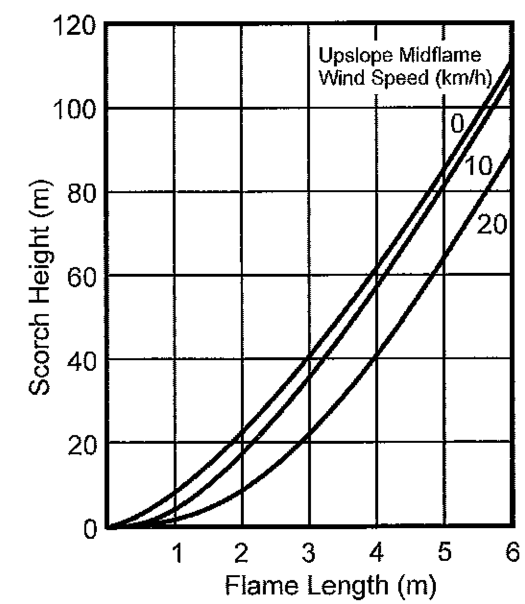

Figure 2.10. Graph showing the effects of rising wind speeds on the height of crown scorch, when all other environmental conditions are held constant.

match the original equation when solved for the same conditions (i.e., no wind and 25°C). Further, the correction for wind will only be valid for wind speeds that do not badly distort the convection plume which is itself a function of the intensity of the fire.

2.5.2.5 *Fire spread rate*

The speed of an advancing fire will vary over time and location due to the changing fire environment. The fire environment is the sum total of the surrounding conditions, influences, and modifying forces of topography, fuel, and weather that determine fire behavior (Figure 2.1). Fire will spread more rapidly through drier fuels, up slopes, and in the direction of the wind.

Fire spread rate measures the speed of an advancing fire front. The spread rate will govern how much area is burned by the fire during any time interval. Although often determined empirically, the rate of spread (R) can be estimated mathematically (Rothermel, 1972):

$$R = I_R \xi (1 - \varphi_w + \varphi_s) / \rho_b \varepsilon Q_{ig} \qquad (2.6)$$

The terms in the numerator govern energy release (exothermic factors):

I_R = reaction intensity (total heat release rate per unit area of fire front);
ξ = propagating flux ratio (proportion of heat that heats adjacent fuel);
φ = wind and slope multipliers (empirical factors).

The denominator terms comprise the endothermic (energy-absorbing) combustion reaction:

$\rho_b \varepsilon$ = effective bulk density (ε is the effective heating number, ~1 for fine fuels, decreasing with fuel size);
Q_{ig} = heat of preignition (energy per unit mass required for ignition).

In this combustion reaction, the most dynamic terms will be φ_w, which expresses the effect of the changing wind, and Q_{ig} which is largely a function of fuel moisture. One key point to recognize is that the spread rate of a fire is inversely proportional to the amount of energy required to ignite the fuels.

2.5.2.6 *Flame depth*

Flame depth refers to the depth of the spreading fire front. It extends from the leading edge of the flame to the trailing edge that is actively spreading with the fireline (Figure 2.7).

2.5.2.7 *Residence time*

The residence time of a fire is the period of time that a fire persists at any one point. The residence time will be a function of the flame depth and fire spread rate. It is

simply the amount of time it takes the fire to move a distance equal to the flame depth (Albini, 1976; Rothermel and Deeming, 1980; Alexander, 1982).

$$\text{residence time (min)} = \text{flame depth (m)/spread rate (m/min)} \qquad (2.7)$$

Residence time is important for determining the ecological effects of a fire since, in large part, it is the key factor determining the amount of heat transferred into both the ground, and hence roots, and stems of the vegetation by the passing fire. Soil moisture strongly affects how soil temperatures respond to passing fires (Frandsen and Ryan, 1986; Campbell *et al.*, 1995). Moister soils take longer to heat and are therefore highly resistant to temperature change from fast-moving fires, but heat penetration is deeper and lasts longer due to the heat capacity of the water. Longer residence times or more intense fires will result in greater levels and depths of soil heating, potentially killing roots, plant propagules, and soil biota. Ground fires are particularly damaging to the roots of vegetation, despite their low intensities, because residence times can be for hours or even days (Van Wagner, 1983; Hartford and Frandsen, 1992; Hungerford *et al.*, 1995).

The flaming duration of woody fuels has been shown to be a function of particle size (Anderson, 1969; Albini, 1976; Albini *et al.*, 1995), and on the order of 3.15 minutes per centimeter of diameter for the piece. Clusters of woody pieces have been shown to burn at a similar rate whether flaming or smoldering (Harmathy 1972, 1976). However, Costa and Sandberg (2004) found the smoldering rate of individual logs to be one-third to one-tenth as fast as flaming combustion, depending on log moisture content, air temperature, ventilation, and species-dependant density. Logs can smolder for days.

Heat transfer directly into the stems or boles of trees is the main killing mechanism of surface fires in taller, woody vegetation types. Bark is the main protection that shrubs or trees have against cambial kill by a passing fire. The insulating capacity of bark is mostly a function of its thickness (Spalt and Reifsnyder, 1962; Martin, 1963; Peterson and Ryan, 1986; Kauffman and Uhl, 1990; Rego and Rigolot, 1990; Pinard and Huffman, 1997). Thicker bark reduces the rate of heat transfer to a tree bole by a passing fire, potentially preventing the maximum temperature from reaching levels high enough to kill the underlying cambial cells, thereby girdling the tree (Table 2.4). However, since the insulating capacity of bark functions in both directions, thicker barked trees will remain at their elevated temperatures for longer periods of time after the fire passes than thin-barked trees (Figure 2.11). The expected rate of mortality in trees of varying bark thicknesses, as a function of residence time of a passing fire, has been calculated for some temperate species groups (Peterson and Ryan, 1986) and adapted to predict mortality in tropical evergreen forests (Cochrane *et al.*, 1999):

$$\tau_c = \beta x^2 \qquad (2.8)$$

β = temperature-dependent coefficient (min/cm^2);
τ_c = critical fire residence time for cambial kill (min);
x = bark thickness (cm).

Table 2.4. Relationship between ambient temperature (T_a), the coefficient β, and bark thicknesses $\leq$1 cm. Columns are for bark thicknesses between 0.1 cm and 1.0 cm. Rows provide calculation of τ_c (converted to seconds) using temperature-corrected coefficients (β). Values given are the calculated number of seconds until cambial cell death in the presence of fire. The coefficient β is derived from the formulas in Peterson and Ryan (1986) to cover the range of temperatures likely to be experienced in the tropics.

		Bark thickness (cm)									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
T_a (°C)	β	τ_c (s)	τ_c (s)	τ_c (s)	τ_c (s)	τ_c (s)	τ_c (s)	τ_c (s)	τ_c (s)	τ_c (s)	τ_c (s)
20	2.78	2	7	15	27	42	60	82	107	135	167
21	2.73	2	7	15	26	41	59	80	105	133	164
22	2.71	2	7	15	26	41	59	80	104	132	163
23	2.69	2	6	15	26	40	58	79	103	131	161
24	2.65	2	6	14	25	40	57	78	102	129	159
25	2.60	2	6	14	25	39	56	77	100	127	156
26	2.58	2	6	14	25	39	56	76	99	126	155
27	2.54	2	6	14	24	38	55	75	98	124	153
28	2.50	2	6	14	24	38	54	74	96	122	150
29	2.47	1	6	13	24	37	53	72	95	120	148
30	2.43	1	6	13	23	36	52	71	93	118	146
31	2.39	1	6	13	23	36	52	70	92	116	143
32	2.36	1	6	13	23	35	51	69	90	114	141
33	2.32	1	6	13	22	35	50	68	89	113	139
34	2.29	1	5	12	22	34	49	67	88	111	137
35	2.24	1	5	12	21	34	48	66	86	109	134
36	2.20	1	5	12	21	33	48	65	85	107	132
37	2.17	1	5	12	21	33	47	64	83	105	130
38	2.13	1	5	11	20	32	46	63	82	103	128
39	2.09	1	5	11	20	31	45	61	80	101	125
40	2.04	1	5	11	20	31	44	60	78	99	122

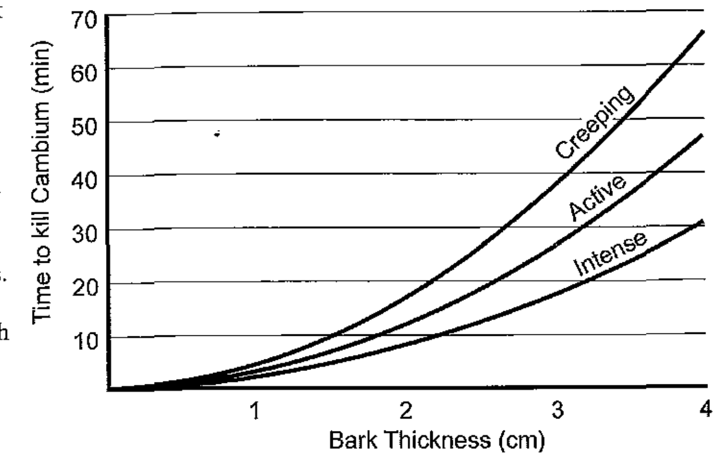

Figure 2.11. Time to kill cambial tissue varies with the square of bark thickness and the difference between the initial (ambient) temperature and the stem's surface temperature, associated with thermal heating which varies with the emissivity of the flames. Emissivity, in turn, increases with the depth of the flames until it approaches unity at around one meter depth.

2.6 FIRE ECOLOGY

Fire ecologists recognize that fire is a natural process, integral to the function of many, though not all, ecosystems. The study of fire ecology focuses on understanding the processes that link fire behavior and ecological effects. This includes the relationships between fire, living organisms, and the physical environment. The effects of a fire (termed fire effects) depend on the intensity, duration, and extent of a fire, as well as the time of year (season) in which it occurs and the amount of time since previous fire(s) (frequency). Whether the effects of a fire are seen as beneficial or destructive depends upon society's point of view and changes with the passage of time since the fire's occurrence. Many ecosystems appear to be totally destroyed by fire but return more vigorously than before, given sufficient time, while others may be radically altered. The main issues addressed in fire ecology are fire dependence, sensitivity and adaptation of plants and animals, fire history, fire regimes, and fire effects on ecosystems.

2.6.1 Fire regimes

The term fire regime embodies the concept that ecosystems are characterized by fires with consistent patterns of behavior, timing, and intervals (Bond and Keeley, 2005). Fire regime characterizations are primarily useful for broad-scale understanding of the role of fire in the structure and function of ecosystems. They are thus appropriate for long-term and strategic planning, and for illustrating changes in fire regimes over time due to either climatic or anthropogenic effects (Morgan *et al.*, 2001; Reinhardt *et al.*, 2001). They can also be very useful for synthesizing information and identifying gaps in our current knowledge (Morgan *et al.*, 2001).

However, Gill (1975, 1998) and Gill *et al.*, (2002) point out that, while fire regime concepts are very useful for describing the normative role of fire in an area, they do not predict the effects of any single fire. Variations in the local fire environment, both within and between fires, can significantly alter the ecosystem impacts of any given fire, shaping the potential behavior of future fires. Given that the fuels present on a site will have been strongly influenced by recent disturbance history (Brown and See, 1981; Furyaev, 1996; Keane *et al.*, 1997; Cochrane *et al.*, 1999; Agee *et al.*, 2000; Finney, 2001; Ryan, 2002), the behavior and effects of any individual fire, or portion thereof, will be dominated by the local fuels, prevailing weather, and position on the fire's perimeter (Gill, 1975, 1998; Catchpole *et al.*, 1982a, b; Gill *et al.*, 2002) (see the fire environment concept—fuels, weather, and terrain, Figure 2.1).

2.6.2 Fire regime characteristics

Fire regimes are typically described in terms of either fire characteristics or fire effects (Agee, 1993; Morgan *et al.*, 2001). Basic fire characteristics that have been used to describe fire regimes include fire extent, season, frequency, and intensity and severity.

2.6.2.1 Fire extent

Fire extent refers to the size of a given fire. In the context of the fire regime, this pertains to the average fire size experienced by the ecosystem over long periods of time. Fires of different sizes can have very different ecological effects. For example, if local seed sources for constituent species are reduced or eradicated from a burn site, ecosystems affected by larger fires may require reseeding by wind-borne or animal-borne dispersal agents from outside of the fire perimeter, greatly slowing regeneration. When considering fire extent, it is important to consider that the area within a fire's perimeter is rarely uniformly burned. The severity of the fire's effects varies within the perimeter due to all of the factors included in the fire environment concept, as well as whether the fire was heading, flanking, backing, or converging (i.e., when two or more flame fronts come together and coalesce into one) when it burned an area of interest (Catchpole *et al.*, 1982a; Cheney and Sullivan, 1997; Ryan, 2002). The size of patches of similar severity matters (Turner and Romme, 1994; Turner *et al.*, 1994, 1997, 1999), as it affects future ecosystem heterogeneity which in turn influences the behavior of future fires.

2.6.2.2 Fire seasonality

Fire seasonality describes the time of year during which fires are most common. The impacts of fires, even of equivalent intensity, can be greatly different depending on the phenological period when they occur. For example, if fires occur during dormant or senescent periods of the vegetation, they will likely be less severe than if they occur just at seed set. The two scenarios could lead to completely different ecosystems establishing in the post-fire environment. In much of the tropics, fires are usually constrained to the dry season or periods of unusual drought (e.g., El Niño or La Niña periods in some regions; Cochrane *et al.*, 1999; Siegert *et al.*, 2001; Page *et al.*, 2002; Alencar *et al.*, 2006; Hoffmann *et al.*, this book).

2.6.2.3 Fire frequency

Fire frequency is a measure of how common fires are in a given ecosystem. It is defined as either the interval between fires at a given site, or the amount of time it takes to burn the equivalent of a specified area with the understanding that some areas may not burn while others burn more than once during a cycle (Van Wagner 1978). The average fire return interval is a landscape or ecosystem characteristic used for defining the fire regime. However, even for similar vegetation types, the fire return interval can vary from region to region or through time. Conceptually, it is therefore more accurate to consider a range of fire return intervals that foster a given ecosystem or landscape configuration. The frequency of fire can have a strong effect on life cycle attributes, species composition, and community structure (Noble and Slatyer, 1980, 1981; Rowe, 1983).

2.6.2.4 Fire intensity and fire severity

Fire intensity is defined as the energy release per unit length of fireline (kW/m). Fire intensity can be estimated as the product of the linear spread rate (m/s), low heat of combustion (kJ/kg), and combusted fuel mass per unit area, or via a flame length correlation (see Section 2.5.2.3). Fire intensity is not directly analogous to fire severity. Fire severity refers to the ecological impact that fires have on ecosystems. It can be defined in many ways but is commonly a measure of plant mortality caused by a fire or the amount of fuel consumption. Fire severity is a function of both the intensity (energy release rate) and duration of a fire. Energy release rates vary throughout the flaming and smoldering phases but are most commonly characterized through flame length–fireline intensity relationships (Rothermel and Deeming, 1980; Alexander, 1982; Ryan, 2002). Duration simply refers to the amount of time that a fire exists at a given point. This is often the same as the residence time of the flame front but in the case of ground fires it may include long periods of smoldering combustion (Hartford and Frandsen, 1992; Hungerford *et al.*, 1995; Ryan, 2002; Reardon *et al.*, 2007). Given that woody fuels and duff burn at relatively constant rates within a fire (Anderson, 1969; Albini, 1976; Frandsen, 1991a, b; Albini and Reinhardt, 1997; Costa and Sandberg, 2004) duration and depth of burn are closely related. Depth of burn is commonly used as a surrogate for measures of duration in field studies of ground fires (Morgan and Neuenschwander, 1988; McCaw *et al.*, 1997; Feller, 1998; Neary *et al.*, 1999; Conard *et al.*, 2002; Chafer *et al.*, 2004).

2.6.3 Fire regime classification

Although fire regimes are a very useful concept, several systems have been proposed for classifying them (e.g., Heinselman, 1978; Agee, 1993; Morgan *et al.*, 1998; Frost 1998), none of which is universally accepted (Figure 2.12). Fire regime classifications can seem arbitrary because they represent artificial partitions of what are actually

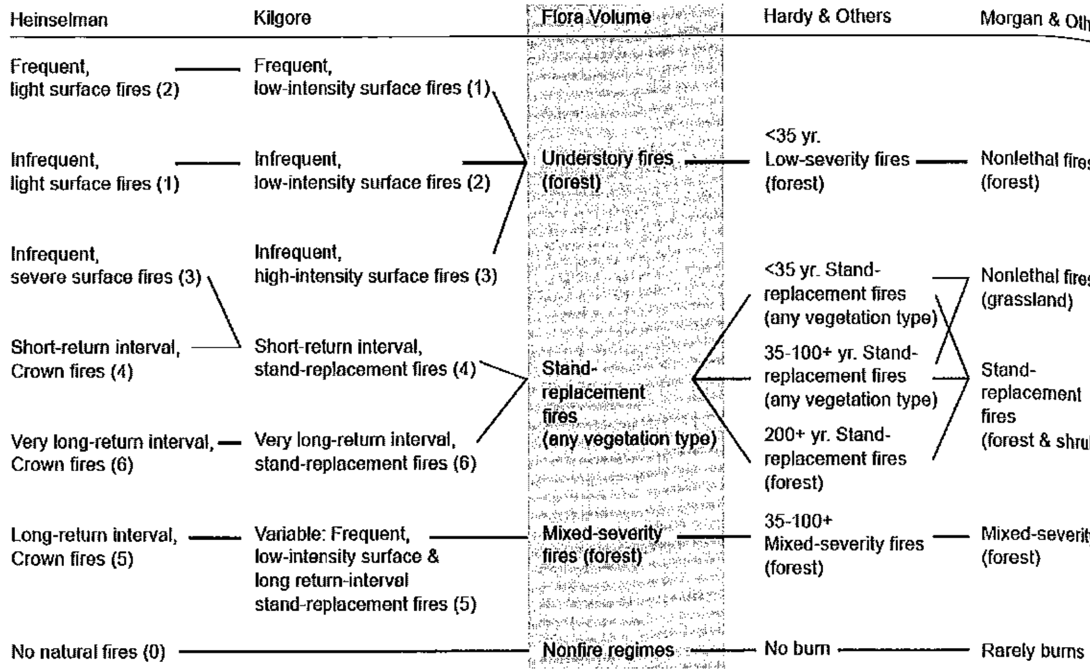

Figure 2.12. Comparison of fire regime classifications by Heinselman (1978), Kilgore (1981), Hardy *et al.* (Morgan *et al.* (1998) with the classification used by Brown and Smith (2000). Lines connect similar fire regime Vegetation types are shown in parentheses; forest includes woodlands, and grassland includes shrublands Brown, 2000).

continuous distributions of natural processes (Brown and Smith, 2000). The use of fire severity as a metric for fire regimes is appealing because it relates fire disturbance directly to its effects (Brown, 2000). However, the considerable temporal and spatial variability in the effects of wildland fires necessitates the use of broad and general classes of fire regimes (Whelan, 1995). In order to be broad-based and widely applicable, a metric should focus on the survival and structure of the dominant vegetation and not site-specific or ecosystem-specific factors (e.g., erosion potential, fuel consumption, etc.). Brown and Smith (2000) use fire severity as the key attribute of a simple fire regime classification system, partitioned as follows:

- *Understory fire regime* (applies to forests and woodlands)—fires are generally nonlethal to the dominant vegetation and do not substantially change the structure of the dominant vegetation. Approximately 80% or more of the aboveground dominant vegetation survives fires.
- *Stand replacement fire regime* (applies to forests, woodlands, shrublands, and grasslands)—fires kill aboveground parts of the dominant vegetation, changing the aboveground structure substantially. Approximately 80% or more of the aboveground dominant vegetation is either consumed or dies as a result of fires.

- *Mixed severity fire regime* (applies to forests and woodlands)—severity of fire either causes selective mortality in dominant vegetation, depending on different tree species' susceptibility to fire, or varies between understory and stand replacement.
- *Nonfire regime*—little or no occurrence of natural fire.

Such fire regime concepts have been used to describe the role of fire in the development and maintenance of species composition and stand structure in major vegetation types ranging from boreal to subtropic (Agee, 1993; Brown and Smith, 2000; Sugihara *et al.*, 2006) but have not yet been expressly extended to tropical ecosystems.

2.6.4 The action of fire in ecosystems

Fire acts as a selective force at the level of the individual organism, either directly, by affecting its ability to continue vital life cycle processes, or indirectly, by altering its habitat conditions (Gill, 1975, 1981; Noble and Slatyer, 1980, 1981; Rowe, 1983; Ryan 2002). Fire can be beneficial, detrimental, or neutral to the individual. In order to predict the effects of fire on individual organisms, it is necessary to integrate the individual's biological characteristics, the fire environment, and the heat transfer mechanisms that couple the physical fire phenomenon to the biota. At the community level, fire effects may be uniform in some ecosystem types or over small regions. However, in many cases, patchiness of fuels will create heterogeneity in fire behavior. This in turn results in spatially variable fire survival, yielding heterogeneous post-fire recruitment, reinforcing the original pattern of fuel patchiness (Bond and Van Wilgen, 1996). Communities are affected to the degree that the sum of their individual constituent biota are affected (Table 2.5).

For example, a creeping surface fire in the understory of a mature tropical pine forest is unlikely to kill the dominant pine overstory trees, but it may be lethal to numerous understory individuals. In the absence of deep, dry organic soil, surface fires can only burn for a limited duration. In natural fuels, most of the surface area is dominated by fine fuels (leaves, grass and 1 h and 10 h time lag fuels). Radiation and conduction of heat from such fires can only kill herbaceous and thin-barked woody plants. The height of crown scorch is predominantly driven by convective heat transport (Van Wagner, 1973) which, in such a fire, is too low to be a source of significant injury to any but plants of very short stature. Therefore, an understory fire regime is established.

The same fire would result in very different results given a decline in fine fuel moisture and/or an increase in either slope or wind speed, since the surface fire intensity would increase. The more intense the surface flaming combustion becomes, the shorter the duration of the fire will be because the fuels are consumed more rapidly. Thus while surface temperatures may be higher, the depth of heat penetration into woody stems or the soil will be less. However, if the fire intensity increases sufficiently, convected heat may scorch the tree canopies and kill even the more resistant overstory trees. Thus, the severity may increase from a non-lethal

Table 2.5. Species attributes relative to early post-fire revegetation (modified from Rowe 1983).

Mode of regeneration and reproduction: first vital process (Noble and Slatyer, 1980)	
Vegetative-based:	
V species	—able to resprout if burned in the juvenile stage
W species	—able to resist fire in the adult stage and to continue extension growth after it (although fire kills juveniles)
Disseminule-based:	
D species	—with highly dispersed propagules
S species	—storing long-lived propagules in the soil
C species	—storing propagules in the canopy
Communal relationships: second vital process (Noble and Slatyer, 1980)	
T species	—tolerants that can establish immediately after a fire and can persist indefinitely thereafter without further perturbations
R species	—tolerants that cannot establish immediately after fire but must wait until some requirement has been met (e.g., need for shade)
I species	—intolerants that can only establish immediately after a fire. Rapid growth pioneers, they tend to die out without recurrent disturbances

understory fire to a mixed severity or stand-replacing fire by virtue of stochastic events (i.e., a change in the weather). Such events can have decade-long to century-long effects on species composition and stand structure.

In comparison, the same creeping low-intensity surface fire may be a mixed severity fire in a closed-canopy tropical forest that is composed of predominantly thin-barked species/individuals. In such forests, only the largest trees have bark thick enough to withstand the fire. Therefore, virtually any fire robust enough to circumnavigate a susceptible tree will girdle and kill the aboveground stem. Survival of individual thin-barked trees is largely driven by the stochastic nature of microvariations in the local fuels and moisture. The mortality associated with such mixed severity fires leads to rapid litter fall and coarse woody debris accumulation. The new accretion of fuels, coupled with the modified surface energy and moisture budgets (Cochrane, this book, a), are such that the area may reburn more intensely, shortly after the initial fire. Recurrent fires such as these can be stand-replacing and have very long-term effects on species composition and stand structure (Cochrane and Schulze, 1998, 1999).

Conversely, in the presence of deep, dry organic soil, the same creeping fire can ignite a ground fire. The overstory vegetation may survive the passing of the surface fire. However, the heat conducted through the soil from the ground fire can kill tissues and organs several centimeters below the mineral soil (Rowe, 1983; Frandsen 1991a, b; Reardon *et al.*, 2007), and kill cambia beneath several centimeters of bark (Ryan and Frandsen, 1991). In consuming the organic soil layer, the fire may both sterilize and expose the underlying mineral soils, leading to a complete change in the potential vegetation that can inhabit the site.

2.6.5 Tropical fire ecology

Fire ecology is the study of how and by what processes fire behavior and ecosystem effects are linked. These linkages are made over a wide range of spatial and temporal scales. Fire's existence depends on a local conjunction of heat, fuel, and oxygen, while fire behavior is a larger scale expression of weather, terrain, and fuel characteristics. By extension, fire regimes are the long-term regional integration of fire's effects within the context of a given climatology, landform, and vegetation (Figure 2.1). Changing any aspect of these relationships will cause an associated ecosystem to adjust its composition, structure, or function to compensate. Likewise, any nonfire-related changes in the ecosystem attributes will alter the fire environment and lead to new fire regimes.

Tropical fire ecology is not a new field of study as much as it is an extension of an existing one. However, tropical fire science has much to add to our global understanding of fire and its effects on ecosystems. The tropics experience more fire than any other region of the planet (Cochrane, this book, b) but they also encompass the vast majority of fire-sensitive ecosystems (Shlisky *et al.*, this book). Between these extremes of the most fire-prone and fire-averse ecosystems exists a whole range of life forms with varied and complex relationships with fire. The remainder of this book explores in detail the ecology of fire in different ecosystems and regions across the tropics.

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Part I

Global overview of fire in the tropics