CHAPTER 1

Strengthening Fire Ecology's Roots

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I. INTRODUCTION

Research on the connection between wildfires and ecological systems goes back to the early discovery that natural disturbances were a recurrent phenomenon in ecosystems and, as such, required an understanding of their effects on ecosystem structure and function. However, connecting wildfires to ecological systems has proceeded slowly. This is probably because forestry and ecology, the two fields primarily interested in wildfire effects on ecosystems, have been sidetracked by their traditional approach to studying ecological systems. Foresters are mostly interested in extinguishing or eliminating wildfires or in managing burns to produce certain effects in the forest (e.g., reduced competition between certain trees or creation of wildlife habitat). Ecologists have been interested in how fires change the composition and structure of ecological systems. The approach that has been taken to investigate these issues has, in general, involved

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describing patterns of fire effects and correlating these to environmental factors. This approach does not immediately lead to a concern with the mechanism of interaction between fire processes and ecosystem processes. One could read the ecological literature for a long time before finding any discussions that indicate an appreciation that *the processes of combustion and heat transfer lie at the heart of fire ecology.*

Fire ecology is a part of both environmental biophysics and ecology. Consequently, it is concerned with combustion, transfer of heat, mass and momentum in wildfires, heat transfer between the fire and the organism, and finally how these physical processes affect ecological processes. In the following chapters, we will not be able to deal with these concerns in any complete manner. Consequently, we have chosen to accent certain topics which we feel ecologists and foresters have not traditionally addressed and about which we believe they should have more information. This means that most of the book is devoted to presenting information on fire processes. The information on ecological effects of fire is more limited than what most ecologists might hope to see. However, this reflects the limitation of our understanding of combustion and heat, mass, and momentum transfer. Particularly lacking are well accepted process-based models for the connection of fire to ecological processes. This has been an ongoing problem noted by several authors over the last decades (Trabaud, 1989; Johnson, 1992; Whelan, 1995; Bond and van Wilgen, 1996).

Readers may be asking at this point: As an ecologist/forester, do I really have to understand all this about combustion and heat transfer? In fact, the purpose of this book is to convince readers of the necessity for understanding the relevant processes involved in the ecological effects of fire. In the absence of a process-based approach, the discipline of fire ecology is left with a collection of case studies, that is, site-specific, species-specific, and also often method-specific correlations between some ecological response and traditionally used fire variables. Thus, there is little justification for the selection of variables and relationships and no way to distinguish between relationships that are physically and ecologically based and those that are statistically significant but spurious.

Central to the approach advocated in this book is that we must invest in a basic understanding of wildfire *materials* and *processes* and their effects on ecological (biological) materials and processes. Materials have properties and are assembled into structures. Thus, in terms of heat transfer from a fire to the living tissues of a tree and its effect on tree mortality, an important material property of bark is its thermal diffusivity. The structure could be considered the changing thickness of bark on different parts of the tree stem. Processes are (natural) phenomena marked by a series of operations, actions, or mechanisms which explain a particular result—in other words, how something works. Some of the wildfire processes are ignition, extinction, flaming and glowing combustion, rate of spread, and fuel drying. Some of the ecological processes affected by fire processes are population dynamics (i.e., birth, death, immigration, and emigration processes), nutrient cycling, and productivity.

II. PROCESSES

Briefly, this book is concerned with the following topics, most of which involve processes. Combustion is considered primarily as the means of generating heat and combustion products such as *smoke* (Chapter 3). *Flames* (Chapter 2) are one of the principal forms of combustion, smoldering being the other. Flames are also the main source of heat by which most wildfires spread. *Fire spread* (Chapters 5 and 6) brings together the different processes in the fire and its environment to explain why it moves. The *plume* (Chapter 7) above the flame is, as often as the flame, the cause of death of organisms. Since *fuel moisture* (Chapters 4) plays such a central role in coupling fire behavior and other environmental variables, it is given special treatment. Although the role of weather and climate has always been recognized as important in wildfires, recent decades have seen some significant advances in our understanding of all scales of interaction of wildfires and the weather. The *coupling of a wildfire and the atmospheric convection* (Chapter 8) above it has only begun but may help us understand better not only fire spread but also some phenomena such as unburned remnants left by fires. *Mesoscale meteorology* (Chapter 9) has shown how fuel moisture is affected by the energy exchange with the regional environment above the ecosystems. *Synoptic scale meteorology and climatology* (Chapter 10) have the longest history in fire ecology, but understanding in recent decades has helped us understand why wildfires occur only under limited kinds of synoptic conditions and how these conditions persist because of midtropospheric circulation patterns in the atmosphere. *Lightning* (Chapter 11) is the major natural cause of wildfires; however, until the advent of lightning locating systems, there was little understanding of the relationship between lightning and wildfire ignition. *Smoldering combustion* (Chapter 13) is a form of combustion that occurs in materials with particular properties (e.g., the partially to well decomposed organic matter (duff) that accumulates on top of the soil in some ecosystems). The process of smoldering is particularly important in ecosystems in which duff removal is necessary for plant regeneration. The *heat transfer to plants* (Chapter 14) uses many of the processes described earlier as input for the transfer into the plant to cause death of the whole plant or necrosis of parts. Many forest landscapes are mosaics of different ages resulting from the overburning of past fires. Determining the *frequency of fires* from this kind of spatial data has proved to be a sophisticated statistical problem (Chapter 12). *Fire management* has undergone changes in past decades from being primarily prevention and suppression to more ecological and economic concerns of understanding and mimicking the fire regime (Chapter 15).

III. TRANSFER RATES AND BUDGETS

The method for studying the preceding processes is generally by use of transfer rates and budgets of heat, mass, and momentum. Heat transfer results from the difference between objects in their average kinetic energies. The mechanisms of heat transfer are radiation, conduction, convection, and latent heat. Radiation is dependent on the temperature of the object. An object's temperature is considered to be proportional to its average kinetic energy. All objects above absolute zero radiate to their surroundings. When fireplaces were an important source of heat in homes, chairs had screens or wings to block the radiation from the fireplace. Thus, radiative transfer depends on the view of the radiating object. Conduction is heat transferred by the motion of adjacent molecules. Solid objects feel warm or cold to us because of conductive transfer between them and our skin. Convection is the mass transfer of heat in a fluid such as water or air as illustrated by hot-air heating systems in homes. Latent heat is the heat absorbed or released when water changes state; for example, evaporation of water absorbs 2450 $J\ g^{-1}$. In their simplest form, these mechanisms consist of the difference in temperature between objects times some coefficient which measures the resistance to transfer.

Mass transfer is the movement of materials and involves diffusion in which different classes of particles have different velocities. Diffusion has two modes: molecular and turbulent. Molecular diffusion is caused by the random motion of molecules, while turbulent diffusion is disorderly movement, often in eddies. Like heat, mass transfer is along a gradient but in this case a gradient of concentration or density rather than temperature. As with heat transfer, diffusion is modified by a resistance term.

Momentum transfer occurs because of resistance to flow in gases and liquids generated by collisions among rapidly moving molecules. Rates of convective heat transfer and of mass transfer are proportional to the viscosity or resistance of the fluid in which they occur. Perhaps the most important issue in momentum transfer discussed in the coming chapters will be boundary layers—the relatively still layer of fluid near solid surfaces in which heat and mass transfer are carried out by molecular diffusion or by boundary layer streaks.

The transfer rates are assembled into budgets which determine the input-output or storage of heat, mass, or momentum based on the law of conservation of energy, mass, and momentum. These budget equations form simple ways of understanding the dynamics of the processes of interest. Ecologists should be familiar with this approach since population dynamics (birth, death, and migration) are budgets which tell us how the numbers in populations come about.

We believe that the reason fire ecologists have not been recruited to the approaches given in the following chapters is the lack of tools to address process questions. This explains why seemingly obvious (to physical scientists) approaches are not taken. Consequently, the approaches used in the following chapters should be of as much interest as the contents.

Some tools are familiar to fire ecologists (e.g., careful measurements, lab and field experiments), but others, such as dimensional analysis (but see Gurney and Nesbit, 1998) and reasoning that seeks to interpret phenomena in light of physical principles, are not. Dimensional analysis helps define what variables should be incorporated and which ones are unnecessary. It also might provide a method for assembling these variables into functional relationships. Experiments (in the widest sense) supply the numerical constants and check the correctness against independent data. Biologists and foresters develop algebraic equations from empirical data by statistical curve fitting, usually with little physiological or biological justification. These functional relationships are simply mathematical descriptions of the data. They often make no dimensional sense. For example, what are the units of fire severity? Experiments are thus used to test classifications of a phenomenon, not the processes involved.

IV. EXAMPLES OF TRADITIONAL VS. PROPOSED APPROACH

Finally, perhaps a comparison between the traditional approach to a problem in fire ecology and the approach advocated in this book would be useful. A tree can be killed by a surface wildfire that has heated its base long enough to kill the cambium beneath the bark. Clearly this process of killing the cambium is affected by the temperature of the surface of the tree, how long this temperature is maintained, and how well the heat is transferred through the bark to the cambium. The question usually asked by ecologists in this situation is: What is the tolerance of different species to surface fires?

The traditional approach by ecologists in studying this fire tolerance has been to heat the base of the tree and record differences in temperature at the cambium (Uhl and Kauffman, 1990; Hengst and Dawson, 1994; Pinard and Huffman, 1997). The tree is heated with a torch, radiant heater, or a burning fuel-soaked rope which is tied around the tree. An unshielded thermocouple is exposed at the surface of the bark, and another is placed in the cambial layer beneath the bark. The temperature course of both thermocouples is recorded during heating.

The time-temperature curve of the outer bark surface (Figure 1) is compared between species, with differences in maximum temperature used to "demonstrate that external bark characteristics can affect heat absorption" (Uhl and Kauffman, 1990). It is not clear how heat absorption could be measured by a

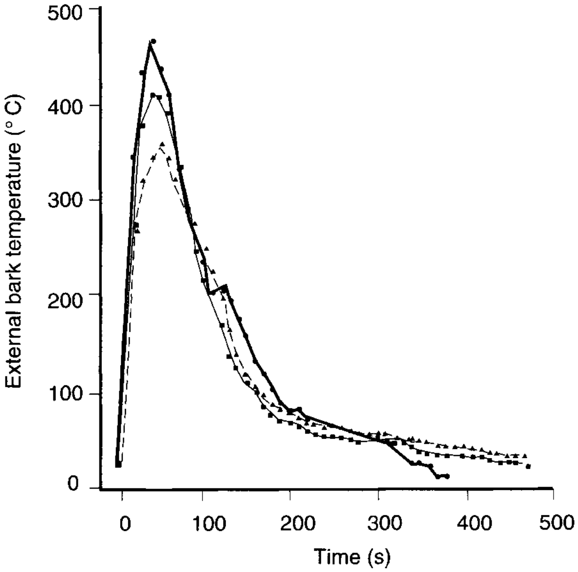

FIGURE 1 Temperature of bark surface during wick (experimental, tree surface) fires of *Tetragastris altissima, Jacaranda copaia,* and *Manilkara huberi* at Vitoria Ranch near Paragominas, Para, Brazil. From Uhl and Kauffman (1990), with permission.

thermocouple at the surface of the bark. Any differences in temperature at the bark surface are probably a result of the experimental setup related to variation in the wick fire and perhaps to flames from the burning bark if this is occurring.

The time-temperature curve of the thermocouple at the cambium surface (inside the bark) is usually related to bark thickness (Figure 2). Time-temperature curves increase more slowly in general with thicker bark species. Notice in Figure 2 that Uhl and Kauffman (1990) use the term temperature flux when the graph gives only temperature. Finally a relationship (Figure 3) is usually given between the maximum cambium temperature and bark thickness (for all species). The equation is then used to calculate the bark thickness at which a tree's cambium will exceed 60°C and cambium death is presumed to happen. Thus, bark thickness is used to infer fire tolerance.

A number of important issues are not considered in such studies. For example, heat transfer is never considered; only temperature is considered. There is no consideration of which heat transfer processes are operating. The transient nature of the heating is never incorporated into the results. Finally, the effect of the material properties of the bark on heat transfer is not considered.

This approach is indeed unfortunate since a more coherent and rigorous approach is almost always given in the references cited by these studies. However,

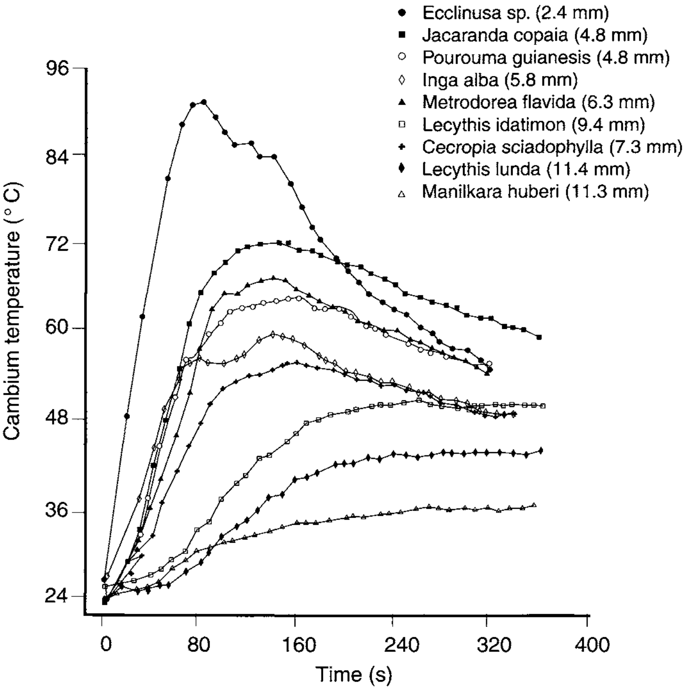

FIGURE 2 Mean temperature flux [sic] at the cambium surface during wick (experimental, tree surface) fires for two individuals (between 20 and 30 cm dbh) in each of nine taxa: *Eclinusa sp.*, *Jacaranda copaia, Metrodorea flavida, Pourouma guianensis, Inga alba, Cecropia sciadophylla, Lecythis idatimon, Lecythis lurida,* and *Manilkara huberi* at Vitoria Ranch near Paragominas, Para, Brazil. From Uhl and Kauffman (1990), with permission. Each species is labeled with the mean bark thickness (mm).

the significance of the heat transfer model (transient heat flow in a semi-infinite solid) given in Spalt and Reifsnyder (1962) does not seem to be recognized. The model (described in detail in Chapter 14) is as follows. Assume that the flame is heating primarily by conduction and that the surface (boundary layer) resistance is minimal, considering the proximity of the flame. The fire suddenly increases the surface temperature. The tree is further assumed to be large enough in diameter so that heating from the opposite side does not affect the cambium (i.e., the main conductive heat transfer is occurring perpendicular to the surface of the bark). The transient heat flow can then be described by

$$\frac{T - T_f}{T_i - T_f} = \mathrm{erf}\left(\frac{x}{2\sqrt{\alpha\tau}}\right) \tag{1}$$

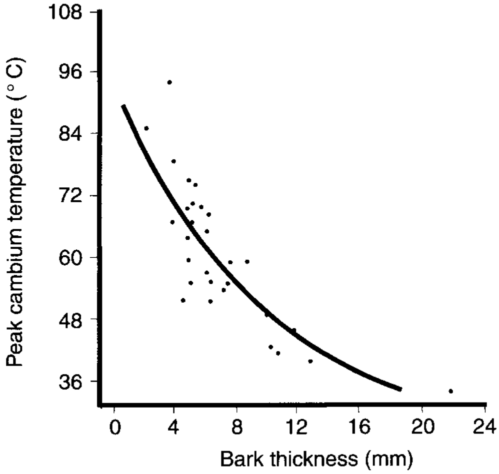

FIGURE 3 The relationship between bark thickness and peak temperature of the cambium during wick fires of 30 individuals distributed among 15 species at Vitoria Ranch near Paragominas, Para, Brazil. From Uhl and Kauffman (1990), with permission.

The left side of Eq. (1) gives the rise in temperature; the numerator gives the difference between the temperature at which the cambium is killed (T) and the flame temperature (T_f), and the denominator gives the difference between the initial (before heating) ambient temperature (T_i) and the flame temperature (T_f). The temperature rise is thus given relative to the initial difference between the flame and tree temperatures. Notice that the gradient of heat is defined by this term. On the right side of the equation, erf is the error function, a value which can be easily looked up in tables for the values in parentheses. The heat transfer is directly proportional to the bark thickness (x) (i.e., the depth for which the temperature gradient is being determined) and inversely proportional to the square root of the thermal diffusivity (α) (i.e., how the bark material affects the flow of heat), and the time it takes for the lethal temperature (T) to be reached (τ). Thus, if we solve for τ, we should be able to see how either trees of different α but same x or different x but same α have different fire tolerances. Thermal diffusivity (α) contains the relevant bark characteristics such as bark density, moisture, and conductivity that influence fire tolerance.

The model we have given is the simplest, and more complicated ones can be formulated (e.g., Costa *et al.*, 1991). However, even this simple model illustrates an approach to the study of fire tolerance that is based on the process (heat conduction) by which the cambium is heated to lethal temperature. This model also provides a rationale for the choice of variables and shows how the variables interact.

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