CHAPTER 13

Duff Consumption

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I. INTRODUCTION

Forest soils (e.g., spodosols) are often characterized by a distinct layer of partially to well-decomposed organic matter lying above the A horizon of the mineral soil. This organic layer consists of three distinguishable horizons: the top L (litter) horizon, composed of the undecomposed litter in which the materials are readily discernible as leaves, twigs, etc.; the middle F (fermentation) horizon, characterized by partially decomposed litter which is still recognizable as to its origins; and the bottom H (humus) horizon of well-decomposed organic matter in which the original structures are no longer discernible (Canada Soil Survey Committee, 1978). The boundary between the F and H horizons can sometimes be quite distinct due to a concentration of white fungal hyphae although in some cases the two horizons are almost indistinguishable from each other (Berg and Ekbohm, 1991). In the forestry and fire ecology literature, the F and H horizons together are generally referred to as duff (e.g., Van Wagner, 1972; Dyrness and Norum, 1983; Merrill and Alexander, 1987), whereas the term *forest floor* generally includes all three horizons (i.e., the litter and duff) (Merrill and Alexander, 1987), but see also Chapter 4, Section II.A.

Consumption of litter and duff by fire has been of interest for some time to foresters and ecologists (e.g., Chrosciewicz, 1959, 1967, 1974; Adams, 1966; Ahlgren, 1970), particularly those working in conifer-dominated forest in cool to cold climates (e.g., boreal and subalpine forest, Douglas fir forests of the Pacific Northwest) for a number of different reasons. Both litter and duff, especially the upper F layer, dry out more rapidly than mineral soil (Van Wagner, 1987). As a result, it has long been observed that seedlings establishing on such substrate are more subject to drought mortality than seedlings establishing on mineral soil. Charron (1998) found that, in the boreal mixedwood forest in Saskatchewan, first-year tree seedling mortality was high enough on litter and the F layer to virtually preclude successful seedling recruitment on these substrates. Successful post-fire tree regeneration in these forests is therefore determined to a large degree by the extent to which duff is removed by fire and suitable seedbed is made available (Chrosciewicz, 1974, 1976; Zasada *et al.*, 1983; Thomas and Wein, 1985; Weber *et al.*, 1987). The extent to which duff is consumed by fire would also influence understory plant mortality due to lethal heating (if not combustion) of roots, rhizomes, and perennating buds of shrubs and herbaceous perennials that are found within the duff (Flinn and Wein, 1977; Hungerford *et al.*, 1995; Schimmel and Granstrom 1996; see also Chapter 14 in this book). Furthermore, as duff is consumed by fire, any dormant seeds that had accumulated within the duff would also be consumed. Therefore, the extent of duff consumption can influence the density and species composition of trees, shrubs and herbs regenerating after a fire. Duff also acts as a reservoir of nutrients for recycling (Weber, 1985; Weber *et al.*, 1985); therefore, post-fire nutrient cycling would be influenced by the presence or absence of duff. Finally, consumption of duff by fire and subsequent mineral soil exposure can leave sites (particularly on steep slopes) vulnerable to soil erosion.

This phenomenon of organic matter consumption in forest fires is not restricted to mid- to high-latitude coniferous forests. Some humid tropical forests develop root mats which are thick layers of litter impregnated with roots (Stark and Jordan, 1978); these forests include high-altitude mountain forests and tropical lowland forests growing on highly weathered acid soils (Kingsbury and Kellman, 1997; Zech *et al.*, 1997). Development of these root mats has been interpreted as an adaptation for nutrient retention (Jordan, 1982; Jordan and Herrera, 1981) as well as a response to aluminum toxicity of the mineral soil (Kingsbury and Kellman, 1997). Litter decomposition, mineralization, and most of the plant uptake of the released mineral nutrients are concentrated in this organic root mat layer above the mineral soil (Stark and Jordan, 1978). The generally larger seeds of tropical tree species, resulting in relatively large seedlings (Richards, 1952), and the abundance of precipitation in the humid tropics suggest that removal of this organic layer may not be a major factor in seedling survivorship as it is in the higher latitude conifer forests. Thus, Kellman and

Meave (1997) found that neither germination nor early seedling survivorship was significantly higher in burned plots than in control plots within the tropical gallery forests in Belize. However, they did find higher seedling densities in plots from which the litter layer had been manually removed and bare soil exposed. Also, given the abundance and concentration of roots in these organic layers above the mineral soil, consumption of this layer by fire would be expected to have a significant impact on plant mortality (both canopy and understory) as well as on nutrient cycling (Stark and Jordan, 1978). Although fire may have been a relatively uncommon phenomenon in undisturbed humid tropical forests (Uhl *et al.*, 1988), it is becoming a more widespread disturbance in the tropics due to changes in land use (Uhl and Kauffman, 1990; Kauffman, 1991). Kauffman *et al.* (1995) noted rootmat consumption in forest clearance fires in the Brazilian Amazon. These human-set fires as well as lightning-caused wildfires from savannas may spread to adjacent undisturbed forests, particularly during unusually dry periods (Leighton and Wirawan, 1986). Extensive rootmat consumption by wildfires has been observed recently in Venezuela (M. Kellman, personal communication) and in the cloud forests of Mexico (J. Meave, personal communication).

The physical/chemical processes involved in the consumption of organic soil horizons by fire are the same regardless of whether they are located in boreal, temperate or tropical forests. This chapter will explain these processes and present some of the models proposed in the combustion literature. However, in order to investigate combustion of any fuel, it is necessary to know something about its chemical composition and physical characteristics.

II. CHARACTERISTICS OF DUFF

Duff is derived from plant litter (leaves, twigs, etc.) which is largely composed of cellulose, hemicellulose, and lignin (Mason, 1976). Both cellulose and hemicellulose decompose much more rapidly than lignin (Alexander, 1977; Berg and Staaf, 1981; Berg *et al.*, 1982); lignin has been described as "the most recalcitrant among organic compounds in litter" (Aber and Melillo, 1991). Thus, the chemical composition of duff shows a gradient with depth of decreasing proportions of cellulose/hemicellulose and increasing proportions of lignin (Berg *et al.*, 1982). In other words, the F layer would have a greater proportion of cellulose/hemicellulose and a smaller proportion of lignin than the H layer. Unlike cellulose, lignin is a complex phenolic macromolecule whose units are not linked in an organized repeating manner; thus the precise structure of lignin is not known, and each lignin molecule may be different (Taiz and Zeiger, 1991). Furthermore, within the plant tissues, lignin is covalently bound to cellulose and other polysaccharides. Although thermal degradation (pyrolysis) and combustion chemistry of cellulose have been well studied (e.g., Lewellen *et al.*, 1976; Moussa *et al.*, 1976; Bradbury *et al.*, 1979; Shafizadeh and Sekiguchi, 1984; Ohlemiller, 1985; 1990a; 1990b), there is much less known about lignin combustion.

Plant litter also contains compounds such as cutin, suberin, and associated waxes plus a host of secondary compounds, generally grouped as terpenes/ terpenoids, phenolic compounds and alkaloids. These secondary compounds are generally specific to a plant species or a related group of species (Taiz and Zeiger, 1991). Thus, the litter and the resulting duff layer would consist of a mixture of compounds that varies spatially both within and between sites, depending on the species composition of the plant community (Berg and Ekbohm, 1991). This heterogeneity in the chemical composition of duff could present challenges in describing its combustion chemistry and attempting to develop general models of its combustion.

The F and H layers also differ in physical characteristics. The H layer is composed of smaller particles and has a higher bulk density than the F layer (Clayton *et al.*, 1977). These differences would influence their thermophysical properties such as conductivity and diffusivity and thus play a role in the rates of combustion propagation in the two layers.

Although very great depths of organic matter can accumulate in waterlogged sites, often creating large peat deposits in mid- to high-latitude wetlands, the thickness of the duff layer in better-drained upland boreal forest generally varies from 5 to 30 cm (Chrosciewicz, 1974, 1989; Dyrness and Norum, 1983; Schimmel and Granstrom, 1996). Green *et al.* (1993) similarly described F + H horizons in various types of coniferous forests on the west coast of North America ranging in depth from 4 to 25 cm and in central Siberia ranging from 8 to 10 cm. Organic root mats in tropical forests have been reported ranging from 0.2 to 10.6 cm (Kingsbury and Kellman, 1997) and from 15 to 40 cm (Jordan and Herrera, 1981). Thus, it would seem that the organic layer in non-wetland forests over a wide range of climatic conditions generally ranges from a few centimeters to 30 – 40 cm in thickness. The thickness of organic matter accumulation in any particular site depends primarily on the decomposition rate which is influenced by temperature and moisture as well as litter quality characteristics such as pH, base content, and presence of polyphenols/ tannins (Williams and Gray, 1974; Mason, 1976; Delaney *et al.*, 1996; Krause, 1998). Between-site differences in microclimate and hydrology and between species differences in litter characteristics thus result in differences in duff thickness between stand types within the same region (Potts *et al.*, 1983; Krause, 1998). For example, in boreal upland sites, *Picea mariana* stands tend to have thicker duff with distinct F and H layers, whereas *Pinus banksiana* stands have thinner duff often with an indistinct H layer (Van Wagner, 1972; Dyrness and Norum, 1983; Miyanishi *et al.* 1999). Also, duff depth depends on time since disturbance (primarily fire or logging). The high-intensity wildfires typical of the boreal forest generally result in some consumption of duff (Wein, 1983; Johnson, 1992). Krause (1998) also reported a significant decrease in duff following logging of a *Pinus banksiana* stand, with minimum levels occurring 6–9 yr after cutting. This postlogging decrease was attributed to the decreased litter input as well as increased decomposition rate due to higher ground temperatures. In the absence of disturbance, duff depths do not continue to accumulate indefinitely; eventually an equilibrium is reached between the rates of litterfall and decomposition. Krause (1998) found that duff accumulation leveled off after 12 years and that the amounts of duff in 12 to 16-year-old stands of *Pinus banksiana* in New Brunswick were not different from those found by Weber *et al.* (1985) in a 53-year-old *P. banksiana* stand in eastern Ontario. Also, Perala and Alban (1982) reported no significant differences in mean duff depths in stands ranging from 40 to 250 years old. Thus, duff depths in the boreal forest appear to reach an equilibrium within the expected interval between fires (Johnson, 1992).

III. EMPIRICAL STUDIES OF DUFF CONSUMPTION

Most studies of duff consumption have focused on measuring and attempting to predict mean values of duff consumption, either in terms of a mean decrease in depth or a mean loss of duff mass (e.g., Blackhall and Auclair, 1982; Dyrness and Norum, 1983; Little *et al.*, 1986; Weber *et al.*, 1987; Brown *et al.*, 1985, 1991; Reinhardt *et al.*, 1989). However, duff consumption within burned forest sites is extremely variable; as Dyrness and Norum (1983) observed after a fire in Alaska, "[t]he sites give the impression of many deeply burned holes scattered among broad areas of unburned or scarcely burned forest floor" (Figure 1). Similar observations have been noted by others (e.g., Zasada *et al.*, 1983). This patchiness in duff consumption appears to be more pronounced as one goes further north in the boreal forest. In terms of regeneration, the important factor is obviously not so much the overall or mean decrease in duff depth but the area of suitable seedbed exposed (Chrosciewicz, 1974, 1976). And since successful seedling recruitment is largely confined to the burned patches or holes in the duff (Charron, 1998), the total area and the spatial patterns of duff burnout would play a significant role in both the density and spatial distribution of tree seedlings in the postfire regenerating stands. These patterns of burned out duff also play a role in the spatial patterns of postfire understory species distribution and composition due to mortality of vegetatively reproducing species that are rooted in the duff as well as in the mineral soil beneath the duff (Flinn and Wein, 1977; Steward *et al.*, 1990; Schimmel and Granstrom, 1996).

To attempt to understand the areal extent and spatial patterns of duff consumption both within and between stands and to determine the factors that

FIGURE 1 Photograph of the forest floor following a fire in a boreal forest site in central Saskatchewan. The burned holes in the duff are clearly defined from the remaining unburned duff.

influence or determine these, it is necessary to understand the processes by which duff is consumed during forest fires. Fuels are consumed by either flaming combustion or smoldering combustion. Flaming combustion is the rapid oxidation of volatiles producing considerable visible radiation (see Chapter 2 in this book for a more detailed discussion). The volatiles in forest fires include terpenes, fats, oils and waxes; these are low-molecular-weight components of fuels that are readily volatilized at low temperatures. More importantly, the flames consume the gaseous pyrolysis products of the principal polymeric constituents of the woody fuels. Smoldering combustion is a nonflaming "slow combustion process in a porous medium in which heat is released by oxidation of the solid" (Schult *et al.*, 1995); it is characterized by thermal degradation and charring of the fuel (Ortiz-Molina *et al.*, 1978). Both forms of combustion involve the coupling of heat generation and heat transfer processes (Ohlemiller, 1985); however, the heat-generating process in flaming combustion is gas-phase oxidation, but it is solid-phase oxidation in smoldering combustion.

Many of the empirical studies on duff consumption make little or no mention of which combustion process is assumed to be operating. The approach in these studies is to produce strictly empirical regression models that attempt to predict duff consumption (decrease in depth or mass) from an assortment of measurable variables such as preburn duff depth and various measures and indices of duff moisture (e.g., Chrosciewicz, 1978a, 1978b; Sandberg, 1980; Blackhall and Auclair, 1982; Brown *et al.*, 1985; Little *et al.*, 1986). The major problem with this approach is that selection of the independent variables is rarely, if ever, justified on the basis of any combustion process by which duff is consumed. Even though many of these studies obtain statistically significant regressions, their empirical models are specific to the site, species, and weather conditions under which their data were collected. For example, Little *et al.* (1986) produced different predictive equations for slash burns within Pacific-Northwest Douglas fir clear-cuts depending on whether the number of days since rain was greater or less than 25 days and also on the presence or absence of a distinct dry layer of duff. Not only do the coefficients differ between these regression models but the predictive variables included in the models also differ. Thus, these studies and models provide little basis for improving our understanding of how duff is consumed or for developing more generalizable models of duff consumption. Furthermore, the lack of any process-based selection of variables in regression models can sometimes lead to trivial results and conclusions. For example, the best fit regression model obtained by Reinhardt *et al.* (1989) had only one independent variable, preburn duff depth. Since duff consumption was fairly complete in their experimental burns, they concluded that "[t]he amount of duff consumed depended mostly on how much was available for consumption."

Since duff consumption can potentially occur by both flaming and smoldering combustion, both processes will be addressed with respect to their role in duff consumption in wildfires.

IV. FLAMING COMBUSTION

The flaming front of a forest fire involves the flaming combustion of fine fuels (Johnson, 1992); flaming combustion is also discussed in Chapters 2, 3, and 5 in this book. Flaming combustion occurs when pyrolytic decomposition of the fuel supplies sufficient volatiles to fuel the flame. Lewellen *et al.* (1976) found that, if cellulose is heated rapidly and the initial products of pyrolysis do not have a chance to react and polymerize (such as if the fuel is a very thin layer of cellulose), it is completely volatilized. Thus, such rapid heating of cellulose would be expected to result in flaming combustion. However, when cellulose is heated slowly, the slow release of volatiles allows them to remain within the fuel matrix for an extended period; repolymerization of the volatiles occurs, producing a solid substance called char. While there may be some initial flaming under such circumstances, the rate of production of volatiles is insufficient to sustain flaming combustion and smoldering of the char residual occurs.

While thin layers of duff or the upper layers of deep duff, if very dry, can be consumed in the flaming front, deeper layers of more decomposed, more compacted duff are unlikely to undergo self-sustained flaming combustion in a wildfire due to their chemical and physical properties. Lignin is less readily volatilized and has a substantially higher char yield than cellulose when heated (Rothermel, 1976; Shafizadeh and DeGroot, 1976; Shafizadeh and Sekiguchi, 1984). The higher lignin:cellulose ratio of duff compared with undecomposed litter would mean a slower rate of release of volatiles. Therefore, heating of deep duff layers in a forest fire is unlikely to produce a sufficient concentration of volatiles to sustain flaming combustion. If flames from other burning objects are impinging on it, the duff can flame initially; however, it will not retain these flames once the external flames vanish.

The degree of volatilization is also influenced by the rate of heating. The rate of heating of duff in a forest fire is influenced by its moisture content. Duff dries out more slowly and therefore generally contains more moisture than litter (except shortly after a light rain that occurs following a long dry period). Thus, often when the litter has dried sufficiently to allow propagation of flaming combustion, the duff may still be quite moist. The latent heat of vaporization required to drive off the moisture in the duff would act as a large heat sink, slowing the rate of its heating by the flaming front.

Finally, according to Rothermel (1972), the rate of heat release of spreading fire per unit area decreases to a very low value as the packing ratio of the fuel approaches 10%. Packing ratio is the ratio of the fuel volume to the total volume of the fuel bed. Since duff has packing ratios greater than 10% (Frandsen, 1991a), the rate of heat generation by its oxidation is generally insufficient to sustain flaming combustion. Thus, as noted in Chapter 6 in this book, combustion of such "thermally thick" fuels has little, if any, impact on the behavior of the advancing firefront.

However, while the duff's contribution of fuel and heat to the flaming front may be relatively insignificant, heat from the flaming front can be the major factor in the smoldering combustion of duff (Van Wagner, 1972), particularly in transient (non-self-sustaining or dependent) smoldering that assumes that the duff is both ignited and consumed by heat transferred downward from the flaming front (Hawkes, 1993).

Van Wagner (1972) presented a heat budget-based model of duff consumption in upland pine stands which assumed such dependent smoldering. Before the temperature of the duff can be raised to its ignition temperature, heat from the fire must first drive off any moisture in the duff. Thus, the model assumes that the processes of heat transfer from the flaming front to the duff, evaporation of any moisture in the duff, and heating of the duff to the ignition point determine the amount of duff consumed.

Since the model assumes that the heat supply to the duff is derived only from downward radiation from the flaming front, this heat flux can be obtained using the Stefan-Boltzmann law:

$$q_{fl} = \varepsilon_{fl}\sigma T_{fl}^4 \tag{1}$$

where q_{fl} is the flux of energy radiated by the flame (W cm^{-2}), ε_{fl} is the emissivity of the flame, σ is the Stefan-Boltzmann constant (5.669×10^{-12} W cm^{-2} K^{-4}), and T_{fl} is the temperature (Kelvin) of the flame. Emissivity is the ratio of the radiative flux emitted by a body to that emitted by a black body at the same temperature, a black body being one that radiates at σT^4. Thus, the emissivity of virtually all heat sources would be some value less than one.

Since the duff is also radiating energy to the flame

$$q_d = \varepsilon_d\sigma T_d^4 \tag{2}$$

the net interchange of radiative energy from the flame to the duff (q) is

$$q = a_d q_{fl} - a_{fl} q_d \tag{3}$$

where a_d is the absorptivity of the duff and a_{fl} is the absorptivity of the flame. Absorptivity is the proportion of incident radiant flux that is absorbed by a body; a black body is a perfect absorber of radiation and has an absorptivity of one.

Substituting Eqs. (1) and (2) for q_{fl} and q_d, Eq. (3) becomes

$$q = a_d\varepsilon_f\sigma T_{fl}^4 - a_{fl}\varepsilon_d\sigma T_d^4 \tag{4}$$

By Kirchhoff's law, $\varepsilon_{fl} = a_{fl}$ and $\varepsilon_d = a_d$; therefore, Eq. (4) can be rewritten as

$$q = a_d\varepsilon_{fl}\sigma(T_{fl}^4 - T_d^4) \tag{5}$$

Van Wagner assumed that duff absorptivity (a_d) was 1, duff ambient temperature (T_d) was 20°C (293 K), and flame temperature (T_{fl}) was 800°C (1073 K). Substituting these values and, by convention, putting the 10^{-12} of the Stefan-Boltzmann constant into the denominator of the temperature terms, Eq. (5) becomes

$$q = 5.669\ \varepsilon_{fl}\left[\left(\frac{1073}{1000}\right)^4 - \left(\frac{293}{1000}\right)^4\right] = 7.473\ \varepsilon_{fl} \tag{6}$$

For the duff to burn, the temperature of the duff must be raised to its ignition temperature. The quantity of heat required for this, H (measured in J g^{-1}) is given by

$$H = Mc_w(1000 - 20) + lM + c_d(300 - 20) + 50.23 = 2585M + 460 \tag{7}$$

The first term represents the energy required to heat the moisture in the duff from its initial temperature (20°C) to boiling point (100°C) where M is the moisture content (% dry wt) and c_w is the specific heat of water (4.18 J g^{-1}).

The second term is the energy required to vaporize this water where l is the latent heat of vaporization (2.25×10^3 J g^{-1}). The third term gives the energy required to heat the duff from 20°C to its ignition temperature of 300°C, where c_d is the specific heat of duff (1.47 J g^{-1} $°C^{-1}$). The final term is the heat of desorption of bound water in the duff (50.23 J g^{-1}).

If the net energy from the flame given by Eq. (6) is equal to the energy required to burn the duff given by Eq. (7), the resulting energy balance can be written as

$$q = \frac{DVH}{w} \tag{8}$$

where D is the mass of duff consumed (g cm^{-2}), V is the rate of advance (cm s^{-1}) of the flaming front, and w is the horizontal thickness or width of the flaming front (cm). Solving for D gives

$$D = \frac{qw}{VH} \tag{9}$$

Since $w/V = \tau$, the residence time (s) of the flaming front, Eq. (9) can be rewritten as

$$D = \frac{\tau q}{H} \tag{10}$$

Although residence time (τ) varies with the fire behavior, for his experimental burns of pine stands Van Wagner assumed a value of 60 s. Substituting this value and Eqs. (6) and (7) into Eq. (10) gives

$$D = \frac{7.473\varepsilon_{fl} \cdot 60}{2585M + 460} \tag{11}$$

In order to be able to predict duff consumption (D) from duff moisture content (M), it is necessary to obtain an expression for ε_{fl}. In lieu of determining ε_{fl} from actual measurements of downward heat flux, Van Wagner used measured values of D and M to obtain estimates of ε_{fl} and then plotted these estimates of ε_{fl} against M, obtaining a straight line relationship:

$$\varepsilon_{fl} = 0.770 - 0.00543M \tag{12}$$

Finally, substituting Eq. (12) for ε_{fl} in Eq. (11) gives

$$D = \frac{7.473(0.770 - 0.00543M) \cdot 60}{2585M + 460} = \frac{345.253 - 2.435M}{2585M + 460} \tag{13}$$

The model showed a reasonable fit to data from 12 experimental fires, 6 in *Pinus resinosa* and *P. strobus* stands and 6 in *P. banksiana* stands (Figure 2). How-

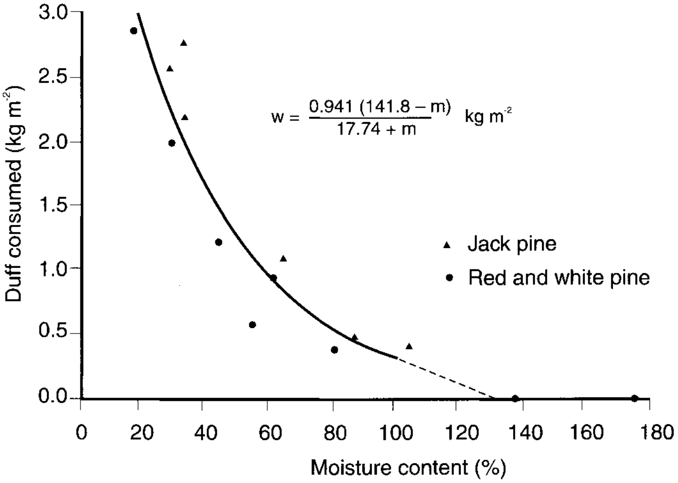

FIGURE 2 Empirical results and model prediction of duff consumption (kg m^{-2}) as a function of percent moisture content. From Van Wagner (1972).

ever, as Van Wagner noted, this fit of the empirical data to the model is not a test of model validity since the estimate of ε_{fl} was obtained empirically from measured values of *D* and *M* and then this estimate was used to obtain the final equation for determining *D* from *M*.

One limitation of the model is its prediction of 7.55 kg m^{-2} as the maximum amount of duff that could be consumed (even at 0% duff moisture which would almost never occur in most forests even under the driest weather conditions). This value converts to a maximum depth of duff that could be consumed of 10.6 cm, assuming a duff bulk density of 0.071 g m^{-3} (the standard Duff Moisture Code layer in the Canadian Fire Weather Behaviour System is 7 cm deep and 5 kg m^{-2} in weight). This maximum depth exceeds the duff depths found in the *Pinus* stands of the Great Lakes–St. Lawrence forest for which the model was developed and, therefore, may not be unreasonable. However, without some modification, the model would obviously not be generalizable to boreal forest stand types with deeper duff depths, such as *Picea mariana* stands. This limit also suggests that heat transfer from the flaming front may not be the main process driving duff consumption observed in stands with deep duff layers.

Despite some of the questionable assumptions and limitations, Van Wagner's (1972) model is notable for its process approach to modeling duff consumption, in contrast to almost all of the previous and subsequent studies in the forestry literature that have taken a strictly empirical approach.

Hawkes (1993) noted that this model did not take into account any heat generated by the combustion of the duff itself. Therefore, he modified Van Wagner's model by adding heat transfer from the combustion zone in the duff. Based on six temperature histories of smoldering in peat, he assumed an average temperature of 400°C for the duff combustion zone and used the Stefan-Boltzmann law to estimate this second heat source. As in the Van Wagner model, Hawkes' model assumes that all heat transfer is by radiation and does not consider conduction or convection. In testing this revised model in the lab using a propane burner as the heat source and peat as the fuel, Hawkes obtained a reasonably good fit between the predicted and measured depths of burn (converted from the weight of duff consumed). However, because he was interested only in dependent smoldering (such as might occur in slash burns), he limited the moisture levels of his samples to those that would not allow self-sustaining smoldering combustion (i.e., a minimum duff moisture content of 220%). Van Wagner's (1972) model predicted no duff consumption when the moisture content is greater than 134% because beyond that moisture level, the surface litter fuels would not carry a burn. Thus, the usefulness of Hawkes' model to more realistic conditions in fires (whether natural or prescription set) may be questionable. The problem was that at lower fuel moistures, self-sustained smoldering occurred in the deep fuel beds. This suggests that in most forest fires duff would not be consumed only during passage of the flaming front. In fact, studies have found that duff consumption more typically occurs by self-sustained smoldering combustion *after* passage of the flaming front (e.g., Wein, 1981; 1983; Hungerford *et al.*, 1995). This may also partially explain why studies of experimental burns have not been able to find a strong relationship between fire intensity and duff consumption (e.g., Alexander, 1982).

Since the physical and chemical characteristics of duff, in fact, make smoldering combustion more likely than flaming combustion (as discussed earlier), and since smoldering is now generally recognized as the major process responsible for duff consumption in forest fires (Frandsen, 1991b; Johnson, 1992; Hungerford *et al.*, 1995), the next section will explain the process of smoldering and discuss some of the models that have been proposed for this process.

V. SMOLDERING COMBUSTION AND PYROLYSIS

Smoldering has been defined as "a self-sustaining, low temperature combustion process involving pyrolysis of the substrate ahead of a solid-phase combustion front" (Shafizadeh *et al.*, 1982). It is characterized by thermal degradation and charring of the solid material with evolution of smoke (Moussa *et al.*, 1976). Because it sometimes involves emission of visible glow, smoldering has also been referred to by some as glowing combustion (Williams, 1977; Johnson, 1992).

However, Drysdale (1985) makes a distinction between glowing combustion and smoldering and, although glowing combustion "is associated with the surface oxidation of carbonaceous materials," it differs from smoldering in that "thermal degradation of the parent fuel does not occur, nor is it required." On the other hand, if glowing combustion specifically refers only to the process of surface oxidation of a solid, it may be viewed as the final stage of the smoldering process (Simmons, 1995). Only porous materials which form a solid carbonaceous char upon thermal degradation are capable of self-sustained smoldering combustion (Drysdale, 1985). Duff as well as organic peat soils are capable of such sustained smoldering (Frandsen, 1987, 1991a,b; Hawkes, 1993; Hungerford *et al.*, 1995).

A large number of studies have been conducted on smoldering in various materials such as dust/sawdust (Cohen and Luft, 1955; Palmer, 1957), cigarettes (Egerton *et al.*, 1963; Muramatsu *et al.*, 1979; Yi and Kim, 1996), rolled cardboard/paper and incense sticks (Kinbara *et al.*, 1967; Sato and Sega, 1985), polyurethane foam (Ohlemiller *et al.*, 1979) and cellulose (Lewellen *et al.*, 1976; Moussa *et al.*, 1976; Ohlemiller, 1985, 1990a,b). Few, if any, studies appear to have been conducted on smoldering in duff, although one study was conducted on packed beds of plant litter (Jones *et al.*, 1994). Therefore, any understanding of smoldering combustion of duff must come from empirical studies and theoretical models of smoldering in other materials that have been better studied. A number of lab studies on smoldering have used peat as a substitute for forest duff with the justification that peat has similar particle sizes and bulk densities as duff (Frandsen, 1987, 1991a,c; Hartford, 1989; Hawkes, 1993). Dried commercial peat generally consists of 95% organic matter (Hawkes, 1993). Using Curie-point pyrolysis-mass spectrometry, Bracewell and Robertson (1987) showed that the chemical composition of peat was very similar to that of the F duff layer. Unfortunately, most of the literature on duff consumption (cited in an earlier section of this chapter) as well as the studies of smoldering in peat mentioned here indicate little awareness of the numerous studies of the smoldering process published in the combustion literature. What follows is an introduction to this literature and is not meant to be a comprehensive review.

Smoldering differs from flaming combustion in its less complete oxidation of the fuel, its lower temperature, and its slower rate of propagation (Ohlemiller, 1985). Ohlemiller noted that, despite wide variation in fuel type and fuel configuration, smoldering velocities do not vary greatly, suggesting that the process is limited by the oxygen supply rate rather than by the fuel oxidation kinetics. Moussa *et al.* (1976) and Williams (1977) had also concluded that smoldering velocities were generally governed by the rate of oxygen diffusion rather than by reaction kinetics. If the rate of oxygen supply is increased sufficiently, smoldering can undergo a transition to flaming combustion (e.g., the use of bellows to revive a dying fire).

As with flaming combustion, smoldering occurs through the coupling of heat release and heat transfer mechanisms. Smoldering is initiated by heating of a porous solid such as cellulosic polymers, resulting in its decomposition and yielding char and volatiles. Char is "the black solid residue of a variable aromatic nature remaining after the end of the initial rapid weight loss upon heating of a polymer" (Ohlemiller, 1985). Pyrolytic degradation of polymers such as cellulose is exothermic if oxygen is available or endothermic in the absence of oxygen; both processes produce char which then reacts with oxygen in an exothermic reaction. Sustained propagation of smoldering depends on sufficient heat from the exothermic reactions being transferred ahead of the smoldering zone to result in pyrolysis of the virgin fuel and exposure of fresh char which can then oxidize (Drysdale, 1985). Thus, pyrolysis and char production are essential steps in smoldering combustion.

Pyrolysis temperatures for the three main constituents of duff differ: hemicellulose 200–260°C, cellulose 240–350°C, and lignin 280–500°C (Roberts, 1970). Lignin requires higher temperatures and yields less volatiles and more char than cellulose (Shafizadeh and DeGroot, 1976; Drysdale, 1985). The pyrolysis of cellulosic materials has been extensively studied (e.g., Broido, 1976; Lewellen *et al.*, 1976; Shafizadeh and DeGroot, 1976; Bradbury *et al.*, 1979; Shafizadeh *et al.*, 1982; Shafizadeh and Sekiguchi, 1984); therefore, most of the following section on pyrolysis will come from studies of cellulose pyrolysis. Pyrolysis is also discussed in Chapters 2 and 3 in this book.

Low temperature pyrolysis of cellulose produces a large variety of end products including CO_2, CO, CH_4, C_2H_4, H_2, H_2O, low-molecular-weight organic acids, and levoglucosan (Shafizadeh and DeGroot, 1976). Lewellen *et al.* (1976) proposed that, with decreased heating rate, these products of pyrolysis have a longer residence time within the pyrolyzing matrix. This extended period of contact between the primary products allows their repolymerization, cracking or cross-linking to produce char. Thus, Lewellen *et al.* (1976) and Bradbury *et al.* (1979) found that char yields decreased with increased heating rate (e.g., from 20% of original cellulose weight at $\sim 300°C\ s^{-1}$ to 2% at $\sim 1500°C\ s^{-1}$). With an appropriate heating rate, thin samples of cellulose can be completely volatilized with no production of residual char. Besides rate of heating, char formation is also a function of particle size and the presence of moisture and inorganics; larger particle size and the presence of moisture and inorganics increase the yield of char (Shafizadeh and DeGroot, 1976). Thus, the relatively large particle sizes in duff, the presence of duff moisture, and the relatively slow heating rate in a forest fire would be expected to result in high char yields from duff.

Although studies of pyrolysis of cellulosic materials indicate the extreme complexity of the process, Bradbury *et al.* (1979) found that the pyrolytic gasification of cellulose could be described by either a two- or three-step reaction scheme, depending on the temperature range (Figure 3). At higher tempera-

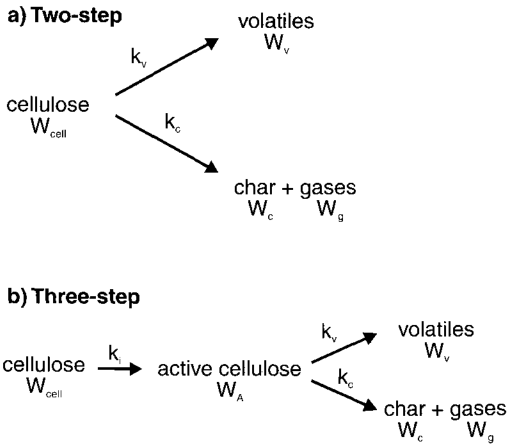

FIGURE 3 (a) Two-step and (b) three-step reaction schemes for pyrolytic gasification of cellulose where W refers to the normalized weights of the respective materials—cellulose (cell), activated cellulose (A), volatiles (v), char (c), and gases (g)—and k refers to the rate constants. From Bradbury *et al.* (1979). A kinetic model for pyrolysis of cellulose. *J. Appl. Polm. Sci.* 23, 3271–3280. Copyright © 1979 John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.

tures, pyrolysis of cellulose can be modeled as two competitive first-order reactions (Figure 3a) with the following rate equations:

$$\frac{-dW_{cell}}{dt} = (k_v + k_c)[W_{cell}] \tag{14}$$

$$\frac{dW_c}{dt} = 0.35k_c[W_{cell}] \tag{15}$$

where W_{cell}, W_v, W_c, and W_g are the normalized weights of cellulose, volatiles, char, and gases respectively (i.e., $W_{cell} + W_v + W_c + W_g = 1$). The rate constants, k_v and k_c, can be expressed by the following Arrhenius relationships:

$$k_v = 1.9 \times 10^{16} \exp\left(-\frac{47{,}300}{RT}\right) \text{min}^{-1} \tag{16}$$

$$k_c = 7.9 \times 10^{11} \exp\left(-\frac{36{,}600}{RT}\right) \text{min}^{-1} \tag{17}$$

where R is the universal gas constant and T is temperature. The numerical values are the preexponential factor and activation energy for each reaction and would be specific to the reaction. Temperature (T) at time t is given by

$$T = T_f - (T_f - T_0)\exp(-2.92t) \tag{18}$$

where T_f is the final pyrolysis temperature and T_0 is the initial temperature.

For lower temperatures where an initial period of accelerating weight loss is observed, Bradbury *et al.* (1979) proposed a model involving three reactions (Figure 3b); first, an active cellulose is formed by an initiation reaction; then the active cellulose decomposes by two competitive first-order reactions, the first yielding volatiles and the second yielding char and a gaseous fraction. The rate equations for this model are

$$\frac{-d(W_{cell})}{dt} = k_i[W_{cell}] \tag{19}$$

$$\frac{d(W_A)}{dt} = k_i[W_{cell}] - (k_v + k_c)[W_A] \tag{20}$$

$$\frac{d(W_c)}{dt} = 0.35k_c[W_A] \tag{21}$$

where W_A is the normalized weight of active cellulose.

The rate constant k_i can be expressed by the following Arrhenius relationship:

$$k_i = 1.7 \times 10^{21} \exp\left(-\frac{58{,}000}{RT}\right) \text{min}^{-1} \tag{22}$$

Shafizadeh and Sekiguchi (1984) also found that the chemical composition and combustion behavior of cellulosic chars varied with the temperature at which the fuel was heated. Chars formed at lower temperatures had higher concentrations of aliphatic carbons, whereas chars formed at higher temperatures had higher concentrations of aromatic carbons. Aliphatic carbons are more reactive and burn at lower temperatures than the more stable aromatic carbons.

There is some empirical evidence for distinct endothermic pyrolysis and exothermic oxidation zones in smoldering (Muramatsu *et al.*, 1979) which have been incorporated into some smoldering models (e.g., Moussa *et al.*, 1976; Leisch, 1983; Peter, 1992). Separation of pyrolysis and oxidation zones depends on the relative movement of the oxygen supply gas and solid reaction zones. However, Ohlemiller (1985) also cited evidence for both endothermic nonoxidative pyrolysis and exothermic oxidative pyrolysis and proposed that the two processes compete for the virgin fuel (Figure 4). Ohlemiller concluded that "the available evidence points to the likelihood of a significant role for oxidative pyrolysis as an appreciable heat source in many [but not all] smoldering processes." Thus, Kashiwagi and Nambu (1992) and Di Blasi (1995) separated the degradation of cellulosic fuel to char into an endothermic nonoxidative reaction and an exothermic oxidation reaction.

Following pyrolysis of the virgin fuel and the production of char, the next major process involved in smoldering is the exothermic oxidation of the char, producing ash and gases. This process is the primary heat source for the propa-

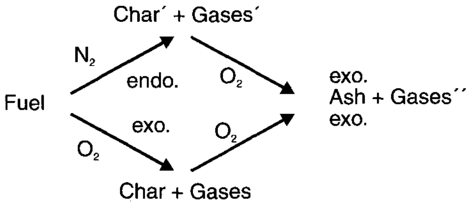

FIGURE 4 Scheme of thermal behavior in smoldering showing the two competing processes by which fuel is pyrolyzed—endothermic pyrolysis in the absence of oxygen and exothermic pyrolysis in the presence of oxygen. Subsequent oxidation of char is exothermic. Reprinted from *Prog. Energy Combust. Sci.*, Ohlemiller, T. J., Modeling of smoldering combustion propagation, pp. 277–310, 1985, with permission from Elsevier Science.

gation of smoldering; therefore, an understanding of smoldering propagation requires an understanding of the factors determining the rate of char oxidation. To identify the mechanisms controlling the propagation of smoldering, Ohlemiller (1990a) looked at the structure (spatial distribution of temperature, oxygen mole fraction, and residual organic mass fraction) of the smoldering wave as it moved laterally through a thick (18-cm) permeable horizontal layer of cellulose insulation; this is an inherently two-dimensional propagation process. Smoldering was initiated on one end face of the fuel layer, and the movement of the smoldering zone was followed by three sets of thermocouples embedded at two depths and at three positions along the fuel as well as by a movable oxygen probe. The distribution of the residual organic mass fraction was obtained by rapidly extinguishing smoldering by smothering with nitrogen and then sectioning the fuel layer. Figure 5 shows the profiles of temperature, oxygen mole fraction and residual organic mass fraction. The length of the smoldering wave was found to be about two to three times greater than the fuel depth (which was 18 cm). Since Palmer (1957) found a comparable ratio of wavelength to fuel thickness for sawdust layers only a few centimeters deep, Ohlemiller (1990a) concluded that similar factors, mainly the rate of oxygen supply, control the rate of smoldering over this range of fuel thicknesses. Figure 6 shows the oxygen inflow paths and heat release zones in a smoldering wave that Ohlemiller inferred from his analysis of the wave structure. He presented a further argument that the shape of the smoldering wave is determined by the rate of oxygen diffusion from above. Leisch (1983) also showed that combustion wave velocity generally decreased with depth in smoldering beds of grain dust and wood dust and concluded that the velocity of smoldering was determined by the net effect of heat generation (determined by oxygen diffusion rate from the surface) and heat loss from the surface.

A distinction is made in the smoldering literature between forward and reverse smoldering, the two limiting cases of one-dimensional smoldering propagation. The reactants in forward (or co-flow) smoldering enter the reaction zone

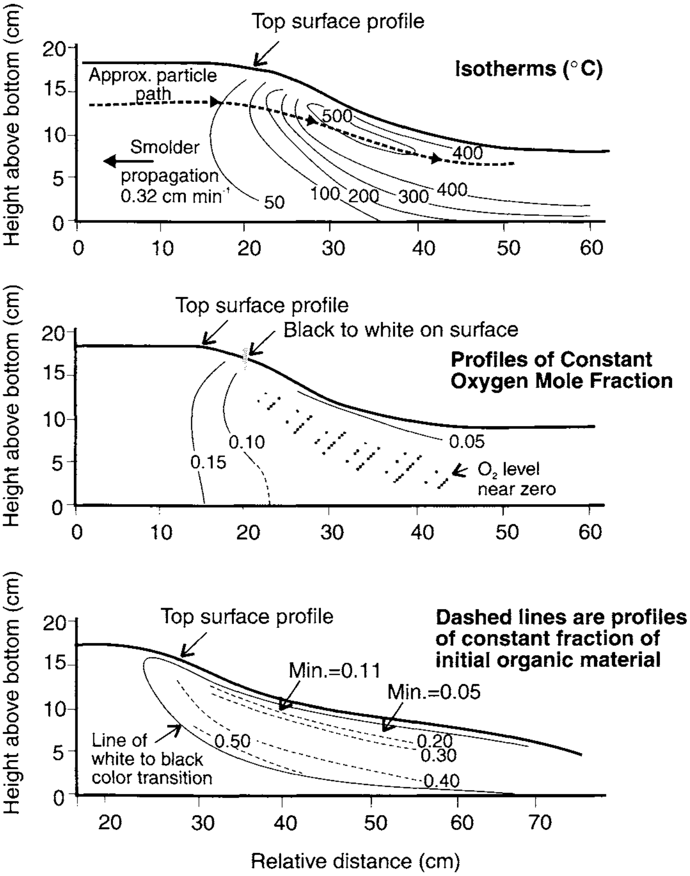

FIGURE 5 Steady state profiles of temperature, oxygen mole fraction, and fraction of remaining organic material superimposed on a cross-sectional view of the smolder wave. Reprinted by permission of Elsevier Science from Smoldering combustion propagation through a permeable horizontal fuel layer, Ohlemiller, T. J., *Combustion & Flame* 81, 341–353, Copyright 1990 by The Combustion Institute.

from opposite sides, somewhat analogous to diffusion flames (Figure 7). The reactants in reverse (or opposed flow) smoldering enter the reaction zone from the same side, somewhat analogous to a premixed flame (Buckmaster and Lozinski, 1996). The horizontal propagation process (Figure 6) has a mixed character. Smoldering studies also distinguish between situations of free flow or forced flow of air/oxygen to the fuel. Smoldering of duff following a forest fire would thus be typically categorized as a free flow forward smoldering process, except near the outward spreading front where it approaches a reverse smoldering character.

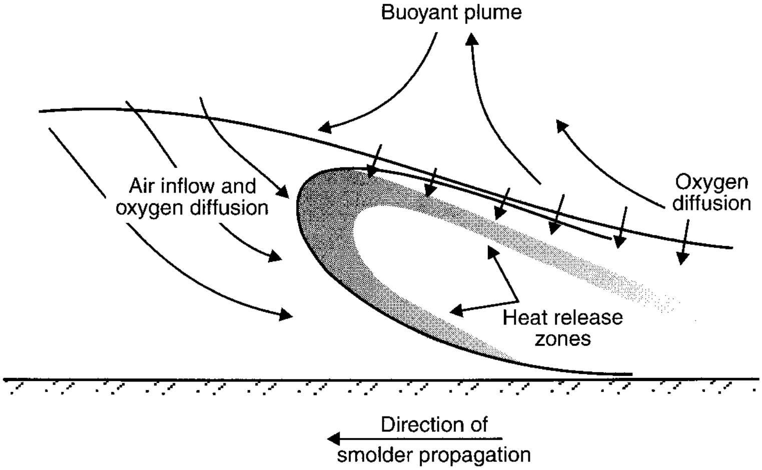

FIGURE 6 Oxygen inflow paths and heat release zones in a spreading smolder wave. Reprinted by permission of Elsevier Science from Smoldering combustion propagation through a permeable horizontal fuel layer, Ohlemiller, T. J., *Combustion & Flame* 81, 341–353, Copyright 1990 by The Combustion Institute.

In summary, the major heat sources involved in smoldering combustion are the processes of oxidative pyrolysis (polymer degradation) and char oxidation, whereas the major heat sinks are the processes of nonoxidative pyrolysis and water movement (Ohlemiller, 1985). Any modeling of smoldering combustion would thus require rate expressions for these reactions as well as for the transfer of heat between the sources and sinks.

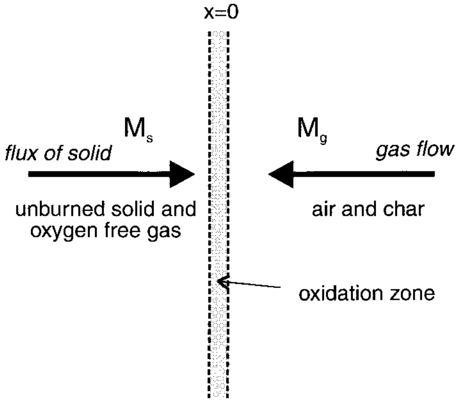

FIGURE 7 Illustration of forward smoldering in which the reactants enter the reaction zone from opposite sides, analogous to a diffusion flame. Reprinted by permission of Elsevier Science from An elementary discussion of forward smolder, Buckmaster, J. and Lozinski, D., *Combustion & Flame*, 104, 300–310, Copyright 1996 by The Combustion Institute.

VI. MODELS OF SMOLDERING COMBUSTION

Various heat transfer models have been proposed for the propagation of smoldering; Drysdale (1985) gives a highly readable description of a couple of the models (Moussa *et al.*, 1976; Williams, 1977), and Ohlemiller (1985) provides an extensive review and evaluation of a large number of models. The simplest models are ones that are based on a greatly simplified heat balance and that derive a simple algebraic equation showing the dependence of smoldering velocity on various parameters (e.g., Cohen and Luft, 1955; Kinbara *et al.*, 1967; Egerton *et al.*, 1963).

As a model of smoldering, Williams (1977) used the fundamental equation for horizontal fire spread through any porous fuel layer, based on application of the energy-conservation principle:

$$q = \rho V \Delta h \tag{23}$$

where q is the net energy flux (W cm^{-2}) across the surface of fire inception, ρ is the bulk density of the fuel (g cm^{-3}), V is the rate of spread of smoldering (cm s^{-1}), and Δh is the thermal enthalpy change (J g^{-1}) in raising unit mass of fuel from ambient temperature to the ignition temperature. To determine the rate of smoldering, this equation can be rewritten as

$$V = \frac{q}{\rho \Delta h} \tag{24}$$

Obviously, in this model, there is no separate consideration of the endothermic/exothermic production of char and the exothermic oxidation of char, nor any consideration of the relative flow direction of air and the reaction zone. The model only considers the net energy flux from these processes. As the net energy flux (q) decreases, the rate of propagation of smoldering decreases.

Assuming that the ignition temperature is not too different from the maximum temperature in the exothermic oxidation zone (T_{max}), then

$$\Delta h = C_{fu}(T_{max} - T_0) \tag{25}$$

where C_{fu} is the heat capacity of the fuel (J g^{-1} °C^{-1}) and T_0 is the ambient temperature (°C). Also, assuming that heat transfer from the exothermic oxidation zone to the endothermic pyrolysis zone is by conduction and that a quasi steady state exists, Eq. (24) becomes

$$V \approx \frac{\lambda(T_{max} - T_0)}{x} \cdot \frac{1}{\rho C_{fu}(T_{max} - T_0)} \tag{26}$$

The term $(T_{max} - T_0)$ cancels out, leaving:

$$V \approx \frac{\lambda}{\rho C_{fu}} \cdot \frac{1}{x} \tag{27}$$

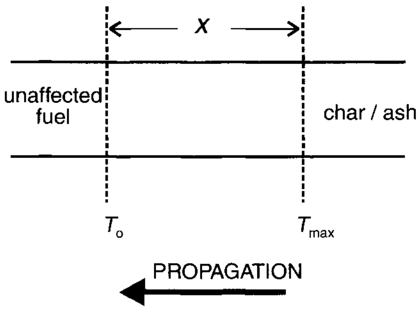

FIGURE 8 Simple heat transfer model for the propagation of smoldering combustion. From Drysdale (1985). Copyright John Wiley & Sons. Reproduced by permission of John Wiley & Sons Limited.

where λ is thermal conductivity of the fuel (W cm^{-1} $^\circ\mathrm{C}^{-1}$) and x is the distance (cm) over which heat is being transferred (Figure 8), which has been found by Palmer (1957) to be on the order of 0.01 m or 1 cm. Thus, according to this model, the rate of propagation is independent of the maximum temperature in the oxidation zone. Furthermore, since thermal diffusivity (α) is defined as

$$\alpha = \frac{\lambda}{\rho C} \tag{28}$$

Eq. (27) can be rewritten simply as

$$V \approx \frac{\alpha}{x} \tag{29}$$

Both Ohlemiller (1985) and Drysdale (1985) note that this model gives very crude estimates and can only be used to give an order of magnitude estimate of the rate of propagation of a smoldering wave; for example, for dry duff, $\alpha \approx 10^{-3}\ \mathrm{cm}^2\ \mathrm{s}^{-2}$ (Marshall and Holmes, 1979). Thus, the estimated rate of propagation of smoldering within dry duff would be of the order of $10^{-3}\ \mathrm{cm\ s}^{-1}$ ($10^{-5}\ \mathrm{m\ s}^{-1}$). Despite this criticism of the model, Jones *et al.* (1994) applied it to smoldering in packed beds of *Casuarina* needles and found that the rate of propagation estimated by the model ($4 \times 10^{-4}\ \mathrm{m\ s}^{-1}$) was remarkably close to the mean propagation rate obtained from six experimental burning trials ($4.7 \times 10^{-4}\ \mathrm{m\ s}^{-1}$). Even though this value is an order of magnitude greater than those reported for smoldering of other lignocellulosic materials, Jones *et al.* attributed this difference to the configuration of the material and the effect of this on the width of the burning zone which they found to be approximately two needle diameters, about 0.001 m or 1 mm, in contrast to the 0.01 m given by Palmer (1957).

A second smoldering model is that presented by Kinbara *et al.* (1967); this model considered downward propagation of smoldering on vertical cylindrical samples (e.g., circular rods of rolled paper or incense sticks) that are exposed to air on all sides. Their model has three assumptions:

1. The heat produced by combustion per unit time is proportional to the rate of air supplied by diffusion which is proportional to $(T - T_0)$ where T is the temperature of the sample and T_0 is the ambient temperature (°C);
2. This heat is inversely proportional to $(T_{ig} - T_0)$, where T_{ig} is the ignition temperature of the sample;
3. A stagnant layer of combustion gases covers the surface of the sample, and both the fresh-air supply to the sample and the heat dissipation from the sample to the air take place at the surface of this layer.

Given these assumptions, Kinbara *et al.* proposed an equation for the propagation velocity (V) of smoldering:

$$V^2 = \left(\frac{4\lambda}{c^2\rho^2}\right)\left(\frac{p}{S}\right)\left(\left[\frac{q}{T_{ig} - T_0}\right] - h\right) \tag{30}$$

where λ is thermal conductivity, c is specific heat, ρ is density of the fuel, S is cross-sectional area of the smoldering solid, p is the periphery of the stagnant layer, h is the heat transmission coefficient, and q is the heat produced by combustion of the solid. As with Williams' model, this model uses only the net heat flux from the endothermic and exothermic reactions involved in smoldering. Kinbara *et al.* found that their model gave a good fit to data obtained from downward smoldering of small (less than 20 mm diameter) fuels (rolled paper and incense sticks). This model was specifically developed to describe smoldering in these very small cylindrical fuels and was not intended to be generalized to other very different fuel configurations such as that found on the forest floor. Thus, the area of the smoldering zone in this model is constrained by the diameter of the fuel, and duff on the forest floor would represent a fuel of virtually infinite diameter. Also, due to convection currents bringing air upward around the periphery of the cylindrical fuel, a cone-shaped smoldering zone develops; this would not be the case for downward smoldering of a semi-infinite fuelbed. However, Kinbara *et al.*'s model represents another relatively simple model of smoldering based on energy conservation principles.

A third model reviewed by Drysdale (1985) and Ohlemiller (1985) is an example of a model that does not use a net heat flux but deals separately with the endothermic pyrolysis of cellulose and exothermic char oxidation. This steady state model of smoldering (again in cellulose cylinders) developed by Moussa *et al.* (1976) assumes that these processes occur in two zones separated by an interface with suitable matching requirements (Figure 9). Also, unlike the pre-

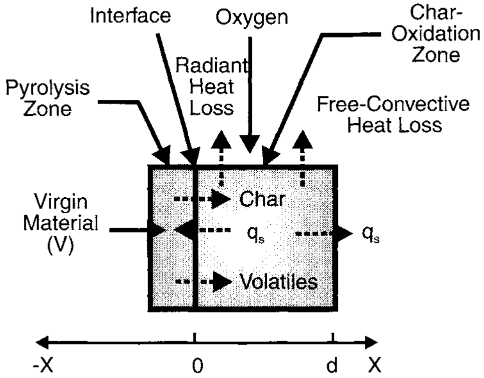

FIGURE 9 Idealized model of smoldering combustion showing heat and mass transports to and from the pyrolysis and char-oxidation zone. From Moussa *et al.* (1976).

vious two models which do not deal with extinguishment, this model can determine the extinguishment limit.

In the first step of this model, the temperature and speed of a steadily propagating pyrolysis zone are determined for a given heat flux at the interface. The major process is conductive heat transfer within the fuel which is undergoing thermal degradation (assumed to be an endothermic process). The governing equations for the cellulose pyrolysis model can be found in the appendix of Moussa *et al.* (1976). The following equation is an approximate closed-form solution that they present for their pyrolysis model:

$$V = \left\{ \frac{\lambda}{\rho_{\infty} c} \frac{F_c}{\ln \Omega} \left[Ei\left(-\frac{E_c}{RT_s}\right) + \frac{F_g}{F_c} Ei\left(-\frac{E_g}{RT_s}\right) - Ei\left(-\frac{E_c}{RT_{\infty}}\right) - \frac{F_g}{F_c} Ei\left(-\frac{E_g}{RT_{\infty}}\right) \right] \right\} \tag{31}$$

where V is propagation speed, λ is thermal conductivity, ρ is density, c is specific heat of the fuel, F_c and F_g are the frequency factors for the char and volatile forming reactions (assumed to occur in parallel), Ω is the ratio of virgin fuel density at the interface over that at $x \rightarrow -\infty$, E_c and E_g are the activation energies of the char and volatile formation reactions, R is the universal gas constant, and the interface temperature $T_s = T_{\infty} + q_s/(\rho_{\infty} c V)$. $Ei(x)$ is the exponential integral function whose values can be obtained from books of standard mathematical tables (e.g., Beyer, 1991). The first term (outside the square brackets) represents heat transfer which is assumed to be solid-phase conduction within a semi-infinite slab and is dependent on the thermophysical properties of thermal conductivity (λ), density (ρ), and specific heat (c) of the fuel (see further discussion of conduction in Chapter 14 in this book). The terms within the square brackets are a result of the pyrolysis kinetics.

In the next step of the model, the heat flux generated by char oxidation is determined for specified ambient oxygen mole fractions and partial pressures. The reaction rate (k) for char oxidation is represented by

$$k = FP_{O_{2,s}}^{1/2} \exp\left(-\frac{E_c}{RT_s}\right) \tag{32}$$

where F is the frequency factor for char oxidation, $P_{O_{2,s}}$ is the partial pressure of oxygen at the char surface, E_c is the activation energy for char oxidation, R is the universal gas constant, and T_s is the temperature at the char surface.

The oxygen flux at the surface (J_{O_2}) is governed by diffusion through the free-convective boundary layer surrounding the char and is given by

$$J_{O_2} \simeq 2.2 \times 10^{-5} \sqrt{\frac{T_m}{\delta}} \frac{(P_{O_{2,\infty}} - P_{O_{2,s}})}{P} \tag{33}$$

where T_m is the mean temperature at the boundary layer, δ is the average thickness of the boundary layer, $P_{O_{2,\infty}}$ and $P_{O_{2,s}}$ are the partial pressures of oxygen at $x \to -\infty$ and $x = 0$, respectively, and P is pressure.

The steady partial pressure of oxygen at the char surface can be obtained by equating its rate of arrival [Eq. (33)] with its rate of consumption, which is given by Eq. (32) times a stoichiometric ratio, ϑ, according to the reaction $C + O_2 \to CO_2$. To obtain the heat flux generated by char oxidation, the rate of char reaction [Eq. (32)] is multiplied by its heat of combustion (32 kJ g^{-1}).

Finally, the heat flux (q_s) available for pyrolysis is the heat flux generated by char oxidation (q) minus heat loss by radiation and free convection to the surroundings through the circumferential area and by conduction to the residual char through the cross-sectional area:

$$q_s \pi \frac{d^2}{4} = \frac{1}{2}(\pi d^2 \cdot (q - \varepsilon \sigma T_s^4 - h(T_s - T_\infty))) \tag{34}$$

where d is the diameter of the fuel sample, T_s is the temperature at the oxidizing surface ($x = 0$), T_∞ is the temperature at $x \to -\infty$, and h is the free-convection heat transfer coefficient (McAdams, 1942; see also Chapter 14 in this book). The heat loss by conduction to the residual char is assumed to equal the feedback heat flux available for pyrolysis. By matching the available heat flux with that required for pyrolysis, the steady smoldering speed and temperature and the extinguishment limit can be determined as shown in Figure 10. When the feedback heat flux does not intersect the curve for the heat flux required for propagation of pyrolysis, extinguishment occurs (as shown with the inverted U-shaped dashed curve). When the two curves are tangential, the extinguishment limit is predicted. The intersections of the two curves give two solutions; only the upper solution is stable. Thus, the usefulness of this model is

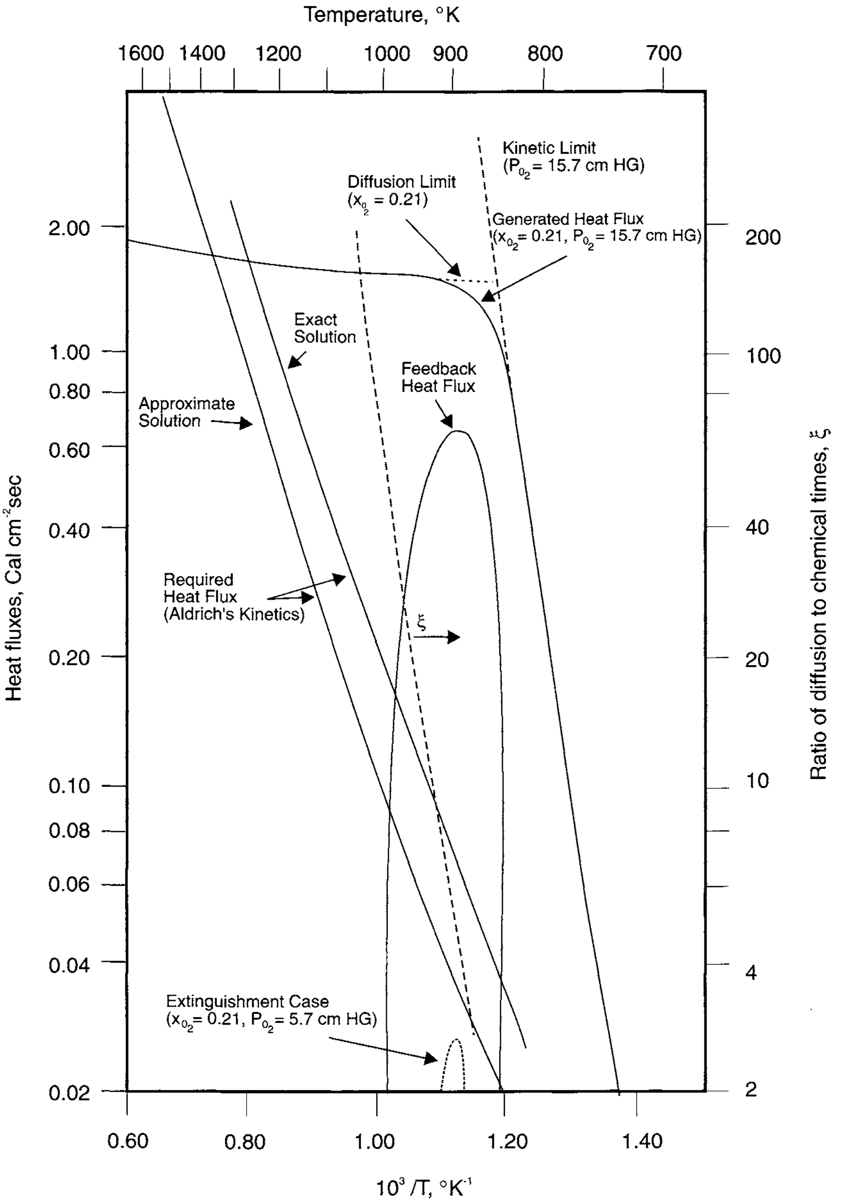

FIGURE 10 Heat fluxes versus inverse temperature where X_{O_2} is oxygen mole fraction and P_{O_2} is oxygen partial pressure (cm Hg). The feedback heat fluxes are calculated for the case of standard atmospheric conditions (X_{O_2} = 0.21, P_{O_2} = 15.7) and for the extinguishment case (X_{O_2} = 0.21, P_{O_2} = 5.7). Also shown is the approximate solution for the required heat flux for Aldrich's kinetics. From Moussa *et al.* (1976).

that, unlike the previous two models that only determine velocity of the smoldering wave, this one can be used to determine the extinguishment limit.

However, as with the Kinbara *et al.* (1967) model, the direct applicability of the model by Moussa *et al.* (1976) for studies of duff consumption is constrained by the fact that these models were developed for small vertical cylindrical fuels. Smoldering combustion in horizontal dust layers, as modeled by Leisch (1983), would be closer to the situation of smoldering in duff. In Leisch's model, velocity of smoldering is given by

$$V = \frac{\lambda}{\rho C}\frac{T_{max} - T_c}{T_c - T_0}\gamma_{ox} \tag{35}$$

where λ, ρ, and C are the thermal conductivity, density, and heat capacity of the fuel; T_{max} is the maximum temperature in the oxidation zone; T_c is charring temperature, and T_0 is ambient temperature. The value of γ_{ox} is given by

$$\gamma_{ox} = \frac{(\text{Surface Area})}{\text{Mass}} P_{O_2}^{1/2} k_{ox} \tag{36}$$

The rate of char oxidation, k_{ox}, is determined by

$$k_{ox} = F_{ox} \exp\left(-\frac{E_{ox}}{RT_{avg}}\right) \tag{37}$$

where $F_{ox} = F_{oxa} + F_{oxg}$, F_{oxa} is the preexponential factor for the oxidation of char to ashes, F_{oxg} is the preexponential factor for the oxidation of char to gases, $E_{ox} = E_{oxa} + E_{oxg}$ (the activation energies for the oxidation of char to ashes and gas), and $T_{avg} = (T_c + T_{max})/2$.

A limitation of Leisch's (1983) model in attempting to understand the development of burned holes in duff is that it is a one-dimensional model. Di Blasi (1995) presented a two-dimensional model of smoldering propagation through horizontal layers of cellulosic particles. In this model, the chemical processes involved in smoldering are modeled as one-step reactions for each main chemical pathway: pyrolytic degradation of cellulose to char and gases, oxidative degradation of cellulose to char and gases, and oxidation of char to ash and gases. The model does not include any gas phase reactions since they are generally not considered of importance in smoldering (Ohlemiller, 1985). The physical processes are then described by energy, momentum, and mass balance equations. The model essentially consists of ten governing equations that are solved numerically (a method of solution is given by Di Blasi, 1994). Simulation results of the model (Di Blasi, 1995) gave profiles of the structure of the smoldering wave in terms of temperature and char density, oxygen mass fraction and solid density, and gas overpressure (Figure 11). These profiles indicated that both

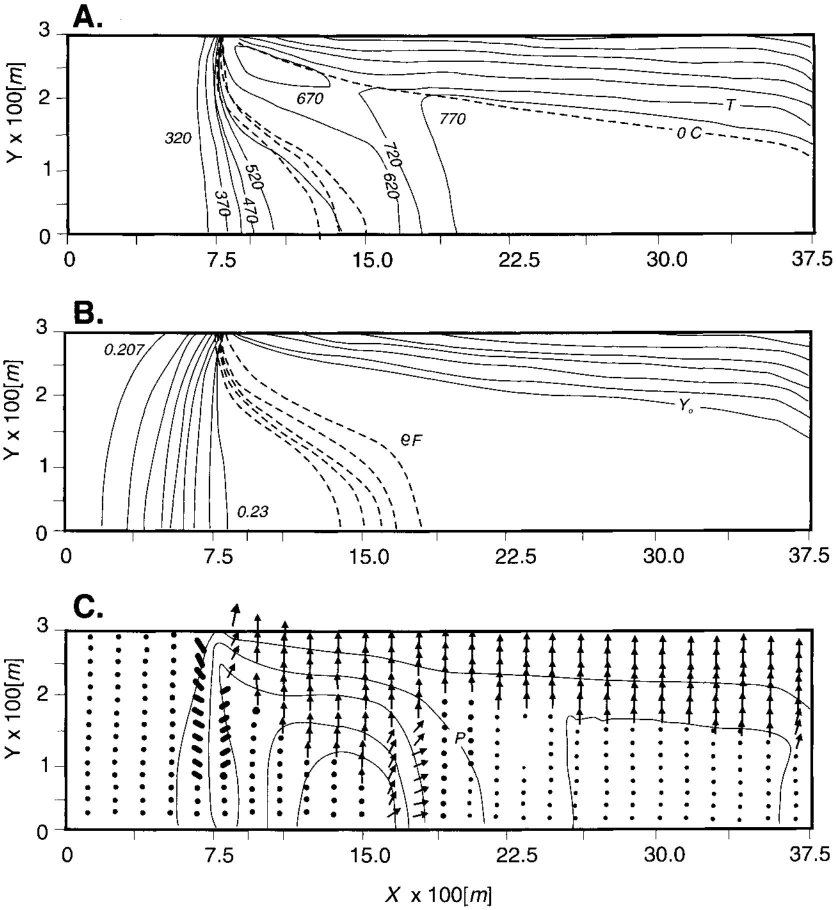

FIGURE 11 Simulated structure of the smoldering wave after 1280 s from ignition: (a) solid lines are contours of temperature (K) in steps of 50 K and dashed lines are contours of char density (kg m^{-3}) in steps of 0.75 kg m^{-3}; (b) solid lines are contours of oxygen mass fraction in steps of 0.023 and dashed lines are contours of solid density (kg m^{-3}) in steps of 6.8 kg m^{-3}; (c) contours of gas overpressure (atm) in steps of 1.5×10^{-3}. From Di Blasi (1995). Copyright Overseas Publishers Association N.V. with permission of Gordon and Breach Publishers.

pyrolytic and oxidative degradation of the fuel occur down to a depth of about 1 cm. Below that depth, only endothermic pyrolysis occurs due to depletion of oxygen. Thus, the solid degradation front advances more rapidly near the surface. However, the maximum reaction rates (and temperatures) occur just beneath the surface where significant amounts of oxygen are still available for both oxidation reactions but where heat loss from the surface is less than at the surface.

Numerous other one- and two-dimensional models of smoldering combustion can be found in the literature (e.g., Egerton *et al.*, 1963; Ohlemiller *et al.*, 1979; Moallemi *et al.*, 1993; Buckmaster and Lozinski, 1996; Yi *et al.*, 1998). Ohlemiller (1985) presented a general model of the thermophysics of propagation which he used to compare and evaluate various models of smoldering combustion propagation. He concluded that all of the models he reviewed, including that of Moussa *et al.* (1976), represented great simplifications of the general model as is evident by the lists of assumptions accompanying each of the models. The usefulness of these models, according to Ohlemiller, is not so much in being good predictive models but "in rationalizing certain experimentally-observed trends." Furthermore, they provide a basis for determining and testing the important factors that influence the rate of smoldering and the extinguishment limits. As noted earlier, without such a physical process basis, empirical studies of duff consumption can provide little justification for selection of variables to measure and can lead to spurious or trivial relationships that do not advance our understanding of duff consumption.

VII. CONTRIBUTION OF SMOLDERING COMBUSTION MODELS TO UNDERSTANDING OF DUFF CONSUMPTION

The purpose of this chapter has been to introduce the reader to some of the combustion literature that would be useful for developing an understanding (and potentially models) of duff consumption by fire. It was not intended to be a comprehensive review or evaluation of the smoldering literature (see Ohlemiller, 1985). There has also been no discussion here of ignition of duff (see Chapters 2 and 11 in this book for more on this topic), and the focus has been on the propagation/extinction of smoldering. It bears repeating that, with few exceptions, empirical studies of duff consumption reported in the forestry and ecological literature indicate no awareness of this extensive body of knowledge on smoldering, the major process by which duff is consumed by fire. Since the typical purely empirical approach results in very site-specific predictive models of duff consumption, the justification for some of these studies appears to be simply that a particular forest type in a particular region has not yet been studied. As mentioned in an earlier section, rarely, if ever, can the empirically derived predictive equations developed for a particular site, forest type, and set of fire weather conditions be used elsewhere and under different conditions. Therefore, rather than more empirical studies of duff consumption using a more or less arbitrary assortment of variables, what is required now is to make use of the available models of the smoldering process as a guide to select more appropriate variables for study and to work on further developments/adaptations of existing models of smoldering to make them useful for the study of duff consumption in forest fires.

Heat transfer and energy-balance-based models all indicate that smoldering can only be propagated and sustained if sufficient heat for pyrolysis is transferred to the virgin fuel from the oxidation zone. Thus, factors that increase heat loss between the oxidation zone and the pyrolysis zone would be important in determining the extinguishment limit. One such factor is the thickness of the fuel layer (Bakhman, 1993). The layer of duff on mineral soil may be seen as a semiopen system consisting of a flat layer of fuel on an inert bed with the other surface (the top) bordering gas (air). For continued propagation of smoldering in any system, heat losses from the reaction zone (char oxidation) must not be too high since sufficient heat for the endothermic pyrolysis of the next layer of duff must be supplied from this reaction zone. The fuel itself acts as insulation, and the thinner the fuel layer, the greater the heat loss from the system. Thus, Bakhman (1993) found that the temperature at which a smoldering wave was initiated decreased with increasing thickness of the fuel. Palmer (1957) found that, at depths greater than the critical minimum depth necessary for sustained smoldering, the rate of smoldering varied with the depth of the fuel layer. He also found that the minimum depth for sustained smoldering increased with increasing mean particle diameter. For cork dust with a mean particle diameter of 2.0 mm, the minimum depth for sustained smoldering was 47 mm. The mean particle size of duff collected from a *Pinus contorta–Picea engelmannii* stand in Alberta was found to be 2.15 mm diameter (Hawkes, 1993). Thus, smoldering may not be sustainable in such duff with depths less than about 50 mm. Jones *et al.* (1994) also reported minimum depths of packed needle fuels that were required for sustained smoldering. This heat loss explanation might also partially account for the finding in some empirical studies that preburn duff depth is a significant factor in duff consumption (Blackhall and Auclair, 1982; Brown *et al.*, 1985; Chrosciewicz, 1978a,b); however, see the earlier discussion of this with regard to the Reinhardt *et al.* (1989) study. Furthermore, it may help to explain the results of Miyanishi *et al.* (1999) who found within the same fire significantly larger burned holes in the duff of *Picea mariana* stands with thicker preburn duff layers than in adjacent *Pinus banksiana* stands with thinner duff. If thickness of the fuel and the subsequent effect on heat loss is a critical factor as proposed by Bakhman (1993), we might expect propagation of smoldering to be more likely in stands with deeper duff, resulting in larger patches of burned out duff. The question then arises: to what extent can within-stand variation in duff depth account for extinguishment of smoldering and thus contribute to the limits of the burned patches?

All the smoldering models require as inputs parameter values for the particular fuel (e.g., density, thermal conductivity, heat capacity, heats of reaction). While values of these properties are available for a similar fuel, peat, and for some of the constituents of duff (particularly cellulose but also lignin to some extent), little information is available on values for duff from various forest types. How much do these properties of duff vary spatially and at what scales is there significant variation? Is within-stand variation as great as between-stand variation? Furthermore, how does spatial variation in these fuel properties compare with the spatial and temporal variation in other significant factors such as fuel moisture? It may turn out that, despite the variation in these fuel properties, the variation in fuel moisture may be so much greater that, for all intents and purposes, some constant values (e.g., mean values for particular forest types) can be used in the models (as is the case with values for fuel chemistry in fire behavior models).

Most of the models also indicate that the rate of oxygen supply (i.e., diffusion of oxygen through the fuelbed from the surface) is the rate-limiting factor for smoldering (Ohlemiller, 1985, 1990a). Also, Moussa *et al.* (1976) concluded that the extinguishment limit would be set by the rate of oxygen diffusion to the char zone. In the case of duff smoldering in a forest fire situation, ignition of the duff would normally occur on the surface (unlike in many of the lab situations described in this chapter where the whole surface of one end of the fuelbed is ignited). Thus, in a forest fire, the smoldering zone would progress both downward and laterally in the duff, creating a hole that extends in size as smoldering continues (Figure 12). The distance between the oxygen source at the surface and the char oxidation zone might thus remain relatively constant, and we would not generally expect smoldering to be extinguished due to a lack of oxygen. One situation in which oxygen might become limiting would be as the smoldering zone approached a region of saturated (water-logged) duff. However, in this situation, it is also unlikely that the heat generated by the char

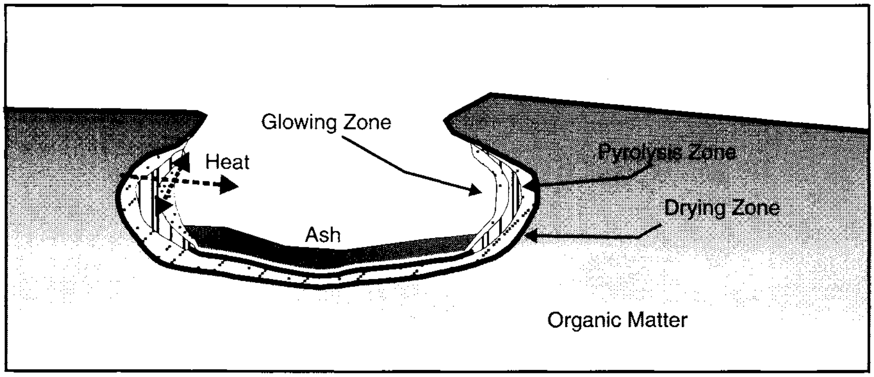

FIGURE 12 Cross-sectional diagram of duff showing the development of a burned hole from smoldering combustion. From Hungerford *et al.* (1995).

oxidation zone would be sufficient to evaporate all the water and raise the temperature of the duff high enough to produce pyrolysis and char formation.

Thus, as has long been recognized, most likely the key factor that determines the extinguishment limit of smoldering in the forest fire situation is duff moisture. Moisture in the duff would result in latent heat flux for evaporation of the water. As noted by Frandsen (1987), the large heat of vaporization of water (2.25×10^3 J g^{-1}) provides a very effective heat sink. Sufficient latent heat flux could result in insufficient heat available for endothermic pyrolysis (charring) of duff, thus resulting in extinguishment of smoldering. According to Yi and Kim (1996), pyrolysis in the region where water evaporation is occurring can be considered negligible. In most experimental situations, the moisture content of the fuel is typically uniform throughout the fuel. However, duff moisture content varies spatially, both within stands and between stands. Thus, further study and modeling of the spatial variation in duff moisture at various scales would be useful.

Bridge and Johnson (2000) showed that the organization of plant communities along moisture and nutrient gradients could be used to relate the spatial distribution of tree species (stand types) to hillslope position and surficial geology. Thus, on glaciofluvial substrate in the mixedwood boreal forest of central Saskatchewan, the ridge tops (which are drier and more nutrient poor) are dominated by *Pinus banksiana,* and the mid to bottom slopes (which are wetter and more nutrient rich) are dominated by *Picea mariana.* Furthermore, duff depths in stands dominated by *Pinus banksiana* are typically significantly less than duff depths in stands dominated by *Picea mariana* (Johnson, 1981; Dyrness and Norum, 1983). Thus, we might expect some correlation between duff depth and hillslope position (i.e., distance from the ridge line). Furthermore, studies have shown that a significant proportion of duff moisture is due to upward transfer of water from the mineral soil to the duff (e.g., Samran *et al.*, 1995). Since soil moisture is influenced by substrate (e.g., glacial till has a higher field capacity than glaciofluvial substrate) and since, within substrate type, soil moisture shows a gradient along hillslopes, it may be possible to use a hydrologic model to predict between-stand variation in duff moisture. With information on between-stand variation in both duff depth and duff moisture, it may be possible to begin to develop a model of variation in duff consumption at the hillslope scale.

At the stand level, Bajtala (1999) found significantly drier duff beneath compared to beyond tree crowns within stands of *Pinus banksiana* and *Picea mariana.* Also, Miyanishi *et al.* (1999) reported a significant spatial correlation between burned holes in the duff and standing boles of trees killed by fire. If duff moisture is the major factor determining extinction of smoldering in forest fires, the patchiness of duff consumption within stands often observed in forest fires would indicate significant variation in duff moisture at this scale. Such variation could potentially be explained by differences in precipitation input due to interception by tree crowns, differences in evaporation as well as dew formation due to crown interception of radiation, and differences in bulk density and moisture-holding capacity of the ground cover (herbaceous/moss cover versus needle litter). Thus, a hydrologically based model of within-stand spatial variation in duff moisture could also be developed. Since such a model would involve the role of the tree canopy in duff moisture dynamics, it could indicate a significant relationship between the areal extent of duff consumption within burned forests and density of trees, particularly those that have a higher interception efficiency (e.g., *Picea* spp. compared with *Pinus* spp.). Finally, the proposed models for duff moisture at the two scales could be combined.

Another aspect that bears further investigation is the interaction between the effects of duff depth and moisture. Recall from the earlier discussion that there exist critical minimum depths of fuelbed required for smoldering propagation resulting from the balance between heat generation from the char oxidation zone and convective heat loss from the surface. Since the process of evaporation of water from the duff is also a heat sink, we might expect the critical depth of fuelbed to increase with increasing moisture content. Thus, McMahon *et al.* (1980) reported sustained smoldering in organic soil blocks with moisture contents as high as 135%. Some preliminary lab studies using varying depths of a peat fuelbed with varying moisture content have, in fact, shown a significant positive relationship as predicted (Miyanishi and Johnson, unpublished data).

Although not exhaustive, the preceding discussions illustrate how an appreciation and understanding of the processes involved in duff consumption and use of smoldering models available in the combustion literature can lead to a somewhat different approach to the study of duff consumption than has been used in the past. This physical process-based approach provides a means of going beyond empirical case studies, leads to more appropriate research questions, and ultimately should result in a better understanding of the phenomenon of duff consumption.

NOTATION

ROMAN LETTERS

C	heat capacity	$\mathrm{J\ kg^{-1}\ K^{-1}}$
D	duff consumption	$\mathrm{kg\ m^{-2}}$
E	activation energy	$\mathrm{J\ mol^{-1}}$
F	frequency factor	$\mathrm{s^{-1}}$
H	heat of reaction	$\mathrm{J\ kg^{-1}}$

J	mass flux	kg m^{-2} s^{-1}
M	moisture content	% dry weight
P	pressure	J m^{-3}
R	universal gas constant	8.314 J mol^{-1} K^{-1}
S	cross-sectional area	m^2
T	temperature	°C or K
V	rate of flaming front advance	m s^{-1}
V	wave speed	m s^{-1}
W	normalized weight	
X	mole fraction	
a	absorptivity	dimensionless
c	specific heat	J kg^{-1} K^{-1}
d	sample diameter	m
h	free-convection heat transfer coefficient	W m^{-2} K^{-1}
k	specific rate of reaction	s^{-1} or min^{-1}
l	latent heat of vaporization	2.25×10^6 J kg^{-1}
p	periphery	m
q	heat flux	W m^{-2}
t	time	s
w	width of combustion zone	m
x	spatial coordinate	m

GREEK LETTERS

α	thermal diffusivity	m^2 s^{-1}
δ	boundary layer thickness	m
ε	emissivity	dimensionless
λ	thermal conductivity	W m^{-1} K^{-1}
ρ	density	g cm^{-3} or kg m^{-3}
σ	Stefan-Boltzmann constant	5.668×10^{-2} W m^{-1} K^{-1}
τ	residence time	s
Ω	ratio of the virgin cellulose density at the interface over that at $x \rightarrow -\infty$, taken to be 10^{-5}	

SUBSCRIPTS

c	char
cell	cellulose
A	active cellulose
d	duff
f	final
fu	fuel
fl	flame
g	gas
i	initial
ig	ignition
max	maximum
v	condensable volatiles
w	water
s	conditions at $x = 0$ (surface)
0	ambient
∞	conditions at $x \rightarrow -\infty$

REFERENCES

Aber, J. D., and Melillo, J. M. (1991). "Terrestrial Ecosystems." Saunders College Publishing, Philadelphia.

Adams, J. L. (1966). Prescribed burning techniques for site preparation in cutover jack pine in southeastern Manitoba. *Pulp Pap. Mag. Can.* 67 **WR:** 574–584.

Ahlgren, C. E. (1970). "Some Effects of Prescribed Burning on Jack Pine Reproduction in Northeastern Minnesota." Miscellaneous Report No. 94. Agricultural Experiment Station, University of Minnesota, St. Paul.

Alexander, M. (1977). "Introduction to Soil Microbiology." John Wiley and Sons, New York.

Alexander, M. E. (1982). Calculating and interpreting forest fire intensities. *Can. J. For. Res.* 60, 349–357.

Bajtala, M. J. (1999). "Spatial Patterns of Duff Consumption in Black Spruce and Jack Pine Stands in the Boreal Mixedwood Forest." M.Sc. thesis, University of Guelph, Guelph.

Bakhman, N. N. (1993). Smoldering wave propagation mechanism. 1. Critical conditions. *Combustion, Explosion and Shock Waves* 29, 14–17.

Berg, B., and Ekbohm, G. 1991. Litter mass-loss rates and decomposition patterns in some needle and leaf litter types. Long-term decomposition in a Scots pine forest. VII. *Can. J. Bot.* 69, 1449–1456.

Berg, B., and Staaf, H. (1981). Leaching, accumulation and release of nitrogen in decomposing forest litter. *Ecol. Bull. (Stockholm)* 33, 163–178.

Berg, B., Hannus, K., Popoff, T., and Theander, O. (1982). Changes in organic chemical components of needle litter during decomposition. Long-term decomposition in a Scots pine forest. I. *Can. J. Bot.* 60, 1310–1319.

Beyer, W. H. (1991). "CRC Standard Mathematical Tables and Formulae," 29th ed. CRC Press, Boca Raton.

Blackhall, J. W., and Auclair, A. D. (1982). Best solution models of prescribed fire impact in subalpine *Picea glauca-Abies lasiocarpa* forests of British Columbia. *In* "Problem Analysis of Prescribed Burning: A Synthesis Text" (A. D. Auclair, Ed.), p. 32. Department of Fisheries and Forestry, Canadian Forest Service, Pacific Forest Research Centre, Victoria.

Bracewell, J. M., and Robertson, G. W. (1987). Characteristics of soil organic matter in temperate soils by Curie-point pyrolysis-mass spectrometry, III. Transformations occurring in surface organic horizons. *Geoderma* 40, 333–344.

Bradbury, A., Sakai, Y., and Shafizadeh, F. (1979). A kinetic model for pyrolysis of cellulose. *J. Appl. Polym. Sci.* 23, 3271–3280.

Bridge, S. R. J., and Johnson, E. A. (2000). Geomorphic principles of terrain organization and vegetation gradients. *J. Veg. Sci.* 11, 57–70.

Broido, A. (1976). Kinetics of solid-phase cellulose pyrolysis. *In* "Thermal Uses and Properties of Carbohydrates and Lignins" (F. Shafizadeh, K. V. Sarkanen and D. A. Tillman, Eds.), pp. 19–35. Academic Press, New York.

Brown, J. K., Marsden, M. A., Ryan, K. C., and Reinhardt, E. D. (1985). "Predicting Duff and Woody Fuel Consumed by Prescribed Fire in the Northern Rocky Mountains." Research Paper INT-337. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden.

Brown, J. K., Reinhardt, E. D., and Fischer, W. C. (1991). Predicting duff and woody fuel consumption in northern Idaho prescribed fires. *For. Sci.* 37, 1550–1566.

Buckmaster, J., and Lozinski, D. (1996). An elementary discussion of forward smolder. *Combust. Flame* 104, 300–310.

Canada Soil Survey Committee. (1978). "The Canadian System of Soil Classification." Publication 1646. Research Branch, Canadian Department of Agriculture, Ottawa.

Charron, I. (1998). "Sexual recruitment of trees following fire in the southern mixedwood boreal forest of Canada." M.Sc. thesis, Concordia University, Montreal.

Chrosciewicz, Z. (1959). "Controlled Burning Experiments on Jack Pine Sites." Technical Note No. 72. Canada Department of Northern Affairs and National Resources, Forestry Branch, Forest Research Division, Ottawa.

Chrosciewicz, Z. (1967). "Experimental Burning for Humus Disposal on Clear-Cut Jack Pine Sites in Central Ontario." Publication No. 1181. Canada Department of Forestry and Rural Development, Forestry Branch, Ottawa.

Chrosciewicz, Z. (1974). Evaluation of fire-produced seedbeds for jack pine regeneration in central Ontario. *Can. J. For. Res.* 4, 455–457.

Chrosciewicz, Z. (1976). Burning for black spruce regeneration on a lowland cutover site in southeastern Manitoba. *Can. J. For. Res.* 6, 179–186.

Chrosciewicz, Z. (1978a). "Slash and Duff Reduction by Burning on Clear-Cut Jack Pine Sites in Southeastern Manitoba." Information Report NOR-X-199. Northern Forest Research Centre, Canadian Forest Service, Edmonton.

Chrosciewicz, Z. (1978b). "Slash and Duff Reduction by Burning on Clear-Cut Jack Pine Sites in Central Saskatchewan." Information Report NOR-X-200. Northern Forest Research Centre, Canadian Forest Service, Edmonton.

Chrosciewicz, Z. (1989). Prediction of forest-floor moisture content under diverse jack pine canopy conditions. *Can. J. For. Res.* 19, 1483–1487.

Clayton, J. S., Ehrlich, W. A., Cann, D. B., Day, H. H., and Marshall, I. B. (1977). "Soils of Canada. Volume 1—Soil Report." Canada Department of Agriculture Research Branch, Ottawa.

Cohen, L., and Luft, N. W. (1955). Combustion of dust layers in still air. *Fuel* 34, 154–163.

Delaney, M. T., Fernandez, I. J., Simmons, J. A., and Briggs, R. D. (1996). "Red Maple and White

Pine Litter Quality: Initial Changes with Decomposition." Technical Bulletin 162. Maine Agricultural and Forest Experiment Station, Orono.

Di Blasi, C. (1994). Smolder spread through thin horizontal fuel layers. *In* "Advanced computational methods in heat transfer III. Proceedings of the Third International Conference" (L. C. Wrobel, C. A. Brebbia and A. J. Nowak, Eds.), pp. 323–330. Computational Mechanics Publications, Southampton.

Di Blasi, C. (1995). Mechanisms of two-dimensional smoldering propagation through packed fuel beds. *Combust. Sci. Tech.* **106**, 103–124.

Drysdale, D. (1985). "An Introduction to Fire Dynamics." John Wiley and Sons, Chichester.

Dyrness, C. T., and Norum, R. A. (1983). The effects of experimental fires on black spruce forest floors in interior Alaska. *Can. J. For. Res.* 13, 879–893.

Egerton, A., Gugan, K., and Weinberg, F. (1963). The mechanism of smoldering in cigarettes. *Combust. Flame* 7, 63–78.

Flinn, M. A., and Wein, R. W. (1977). Depth of underground plant organs and theoretical survival during fire. *Can. J. Bot.* 55, 2550–2554.

Frandsen, W. H. (1987). The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. *Can. J. For. Res.* 17, 1540–1544.

Frandsen, W. H. (1991a). Burning rate of smoldering peat. *Northwest Sci.*, 65, 166–172.

Frandsen, W. H. (1991b). Smoldering spread rate: A preliminary estimate. *In* "Proceedings of the Eleventh Conference on Fire and Forest Meteorology" (P. L. Andrews and D. F. Potts, Eds.), pp. 168–172. Society of American Foresters, Bethesda.

Frandsen, W. H. (1991c). Heat evolved from smoldering peat. *Int. J. Wildland Fire* **1**, 197–204.

Green, R. N., Trowbridge, R. L., and Klinka, K. (1993). "Towards a Taxonomic Classification of Humus Forms." Forest Science Monograph 29. Society of American Foresters, Bethesda.

Hartford, R. A. (1989). Smoldering combustion limits in peat as influenced by moisture, mineral content, and organic bulk density. *In* "Proceedings of the Tenth Conference on Fire and Forest Meteorology" (D. C. MacIver, H. Auld, and R. Whitewood, Eds.), pp. 282–286. Forestry Canada, Environment Canada, Ottawa.

Hawkes, B. C. (1993). Factors that influence peat consumption under dependent burning conditions: A laboratory study. Ph.D. dissertation, University of Montana, Missoula.

Hungerford, R. D., Frandsen, W. H., and Ryan, K. C. (1995). Ignition and burning characteristics of organic soils. *In* "Proceedings of the Tall Timbers Fire Ecology Conference in Wetlands, a Management Perspective" (S. I. Cerulean and R. T. Engstrom, Eds.), pp. 78–91. Tall Timbers Research Station, Tallahassee.

Johnson, E. A. (1981). Vegetation organization and dynamics of lichen woodland communities in the Northwest Territories, Canada. *Ecology* 62, 200–215.

Johnson, E. A. (1992). "Fire and Vegetation Dynamics: Studies from the North American Boreal Forest." Cambridge University Press, Cambridge.

Jones, J. C., Goh, T. P. T., and Dijanosic, M. J. (1994). Smoldering and flaming combustion in packed beds of *Casuarina* needles. *J. Fire Sci.* **12**, 442–451.

Jordan, C. F. (1982). Amazon rain forests. *Am. Scientist* 70, 394–401.

Jordan, C. F., and Herrera, R. (1981). Tropical rain forests: Are nutrients really critical? *Am. Nat.* 117, 167–180.

Kashiwagi, T., and Nambu, H. (1992). Global kinetic constant for thermal oxidative degradation of a cellulosic paper. *Combustion and Flame* 88, 345–368.

Kauffman, J. B. (1991). Survival by sprouting following fire in tropical forests of the eastern Amazon. *Biotropica* 23, 219–224.

Kauffman, J. B., Cummings, D. L., Ward, D. E., and Babbitt, R. (1995). Fire in the Brazilian Amazon: 1. Biomass, nutrient pools, and losses in slashed primary forests. *Oecologia* **104**, 397–408.

Kellman, M., and Meave, J. (1997). Fire in the tropical gallery forests of Belize. *J. Biogeog.* 24, 23–34.

Kinbara, T., Endo, H., and Sega, S. (1967). Downward propagation of smoldering combustion through solid materials. *In* "Eleventh Symposium (International) on Combustion," pp. 525–531. The Combustion Institute, Pittsburgh.

Kingsbury, N., and Kellman, M. (1997). Root mat depths and surface soil chemistry in southeastern Venezuela. *J. Tropical Ecol.* 13, 475–479.

Krause, H. (1998). Forest floor mass and nutrients in two chronosequences of plantations: Jack pine vs. black spruce. *Can. J. Soil Sci.* 78, 77–83.

Leighton, M., and Wirawan, N. (1986). Catastrophic drought and fire in Borneo tropical rain forest associated with the 1982–1983 El Niño Southern Oscillation Event. *In* "Tropical Rain Forests and the World Atmosphere" (G. T. Prance, Ed.), pp. 75–102. AAAS Selected Symposium 101, Westview, Boulder.

Leisch, S. O. (1983). "Smoldering Combustion in Horizontal Dust Layers." PhD dissertation, University of Michigan, Ann Arbor.

Lewellen, P. C., Peters, W. A., and Howard, J. B. (1976). *In* "Sixteenth Symposium (International) on Combustion," pp. 1471–1480. The Combustion Institute, Pittsburgh.

Little, S. N., Ottmar, R. D., and Ohmann, J. L. (1986). "Predicting Duff Consumption from Prescribed Burns on Conifer Clearcuts in Western Oregon and Western Washington." Research Paper PNW-362. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland.

Marshall, T. J., and Holmes, J. W. (1979). "Soil Physics." Cambridge University Press, New York.

Mason, C. F. (1976). "Decomposition." Edward Arnold (Publishers) Ltd., London.

McAdams, W. H. (1942). "Heat Transmission," 2nd ed. McGraw-Hill, New York.

McMahon, C.K., Wade, D. D., and Tsoukalas, S. N. (1980). Combustion characteristics and emissions from burning organic soils. *In* "Proceedings of the 73rd Annual Meeting of the Air Pollution Control Association," Paper No. 80-15.5.

Merrill, D. F., and Alexander, M. E. (1987). "Glossary of Forest Fire Management Terms." Canadian Committee on Forest Fire Management, National Research Council of Canada, Ottawa.

Miyanishi, K., Bajtala, M. J., and Johnson, E. A. (1999). Patterns of duff consumption in *Pinus banksiana* and *Picea mariana* stands. *In* "Proceedings of Sustainable Forest Management Network Conference, Science and Practice: Sustaining the Boreal Forest," pp. 112–115. Sustainable Forest Management Network, Edmonton.

Moallemi, M. K., Zhang, H., and Kumar, S. (1993). Numerical modeling of two-dimensional smoldering process. *Combust. Flame* 95, 170–182.

Moussa, N. A., Toong, T. Y., and Garris, C. A. (1976). Mechanism of smoldering of cellulosic materials. *In* "Sixteenth Symposium (International) on Combustion," pp. 1447–1457. The Combustion Institute, Pittsburgh.

Muramatsu, M., Umemura, S., and Okada, T. (1979). A mathematical model of evaporation-pyrolysis processes inside a naturally smoldering cigarette. *Combust. Flame* 36, 245–262.

Ohlemiller, T. J. (1985). Modeling of smoldering combustion propagation. *Prog. Energy Combust. Sci.* 11, 277–310.

Ohlemiller, T. J. (1990a). Smoldering combustion propagation through a permeable horizontal fuel layer. *Combust. Flame* 81, 341–353.

Ohlemiller, T. J. (1990b). Forced smolder propagation and the transition to flaming in cellulosic insulation. *Combust. Flame* 81, 354–365.

Ohlemiller, T. J., Bellan, J., and Rogers, F. (1979). A model of smoldering combustion applied to flexible polyurethane foams. *Combust. Flame* 36, 197–215.

Ortiz-Molina, M. G., Toong, T-Y., Moussa, N. A., and Tesoro, G. C. (1978). Smoldering combustion of flexible polyurethane foams and its transition to flaming or extinguishment. *In* "Seventeenth Symposium (International) on Combustion," pp. 1191–1200. The Combustion Institute, Pittsburgh.

Palmer, K. N. (1957). Smoldering combustion in dusts and fibrous materials. *Combust. Flame* **1**, 129–154.

Perala, D. A., and Alban, D. H. (1982). "Rates of Forest Floor Decomposition and Nutrient Turnover in Aspen, Pine, and Spruce Stands on Two Different Soils." Research Paper NC-227. USDA Forest Service, North Central Forest Experiment Station, St. Paul.

Peter, S. (1992). "Heat Transfer in Soils Beneath a Spreading Fire." Ph.D. dissertation, University of New Brunswick, Fredericton.

Potts, D. F., Zuuring, H., and Hillhouse, M. (1983). Spatial analysis of duff moisture and structure variability. *In* "Proceedings of the Seventh Conference on Fire and Forest Meteorology," pp. 18–21. American Meteorology Society, Boston.

Reinhardt, E. D., Brown, J. K., and Fischer, W. C. (1989). Fuel consumption from prescribed fire in northern Idaho logging slash. *In* "Proceedings of the Tenth Conference on Fire and Forest Meteorology" (D. C. MacIver, H. Auld, and R. Whitewood, Eds.), pp. 155–160. Forestry Canada, Environment Canada, Ottawa.

Richards, P. W. (1952). "The Tropical Rain Forest: An Ecological Study." Cambridge University Press, Cambridge.

Roberts, A. F. (1970). A review of kinetics data for the pyrolysis of wood and related substances. *Combust. Flame* **14**, 261–272.

Rothermel, R. C. (1972). "A Mathematical Model for Predicting Fire Spread in Wildland Fuels." Research Paper INT-115. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden.

Rothermel, R. C. (1976). Forest fires and the chemistry of forest fuels. *In* "Thermal Uses and Properties of Carbohydrates and Lignins." (F. Shafizadeh, K. V. Sarkanen, and D. A. Tillman, Eds.), pp. 245–259. Academic Press, New York.

Samran, S., Woodard, P. M., and Rothwell, R. L. (1995). The effect of soil water on ground fuel availability. *Forest Sci.* **41**, 255–267.

Sandberg, D. V. (1980). Duff reduction by prescribed underburning in Douglas-fir. Research Paper PNW-272. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland.

Sato, K., and Sega, S. (1985). The mode of burning zone spread along cylindrical cellulosic material. *J. Fire Sci.* **3**, 26–34.

Schimmel, J., and Granstrom, A. (1996). Fire severity and vegetation response in the boreal Swedish forest. *Ecology* 77, 1436–1450.

Schult, D. A., Matkowsky, B. J., Volpert, V. A., and Fernandez-Pello, A. C. (1995). Propagation and extinction of forced opposed flow smolder waves. *Combust. Flame* **101**, 471–490.

Shafizadeh, F., and DeGroot, W. F. (1976). Combustion characteristics of cellulosic fuels. *In* "Thermal Uses and Properties of Carbohydrates and Lignins." (F. Shafizadeh, K. V. Sarkanen, and D. A. Tillman, Eds.), pp. 1–17. Academic Press, New York.

Shafizadeh, F., and Sekiguchi, Y. (1984). Oxidation of chars during smoldering combustion of cellulosic materials. *Combust. Flame* 55, 171–179.

Shafizadeh, F., Bradbury, A. G. W., DeGroot, W. F., and Aanerud, T. W. (1982). Role of inorganic additives in the smoldering combustion of cotton cellulose. *Ind. Eng. Chem. Prod. Res. Dev.* **21**, 97–101.

Simmons, R. F. (1995). Fire chemistry. *In* "Combustion Fundamentals of Fire" (G. Cox, Ed.), pp. 405–473. Academic Press, London.

Stark, N. M., and Jordan, C. F. (1978). Nutrient retention by the root mat of an Amazonian rain forest. *Ecology* 59, 434–437.

Steward, F. R., Peter, S., and Richon, J. B. (1990). A method for predicting the depth of lethal heat penetration into mineral soils exposed to fires of various intensities. *Can. J. For. Res.* **20**, 919–926.

Taiz, L., and Zeiger, E. (1991). "Plant Physiology." Benjamin/Cummings Publishing Company, Redwood City.

Thomas, P. A., and Wein, R. W. (1985). The influence of shelter and the hypothetical effect of fire severity on the postfire establishment of conifers from seed. *Can. J. For. Res.* **15**, 148–155.

Uhl, C., and Kauffman, J. B. (1990). Deforestation, fire susceptibility, and potential tree responses to fire in the eastern Amazon. *Ecology* **71**, 437–449.

Uhl, C., Kauffman, J. B., and Cummings, D. L. (1988). Fire in the Venezuelan Amazon 2. Environmental conditions necessary for forest fires in the evergreen rainforest of Venezuela. *Oikos* **53**, 176–184.

Van Wagner, C. E. (1972). Duff consumption by fire in eastern pine stands. *Can. J. For. Res.* **2**, 34–39.

Van Wagner, C. E. (1987). "Development and Structure of the Canadian Forest Fire Weather Index System." Forestry Technical Report 35. Canadian Forestry Service, Ottawa.

Weber, M. G. (1985). Forest soil respiration in eastern Ontario jack pine ecosystems. *Can. J. For. Res.* **15**, 1069–1073.

Weber, M. G., Hummel, M., and Van Wagner, C. E. (1987). Selected parameters of fire behavior and *Pinus banksiana* Lamb. regeneration in eastern Ontario. *For. Chron.* **63**, 340–346.

Weber, M. G., Methven, I. R., and Van Wagner, C. E. (1985). The effect of forest floor manipulation on nitrogen status and tree growth in an eastern Ontario jack pine ecosystem. *Can. J. For. Res.* **15**, 313–318.

Wein, R. W. (1981). Characteristics and suppression of fires in organic terrain in Australia. *Aust. For.* **44**, 162–169.

Wein, R. W. (1983). Fire behavior and ecological effects in organic terrain. *In* "The Role of Fire in Northern Circumpolar Ecosystems" (R. W. Wein and D. A. MacLean, Eds.), pp. 81–95. John Wiley, New York.

Williams, F. (1977). Mechanisms of fire spread. *In* "Sixteenth Symposium (International) on Combustion," pp. 1281–1294. The Combustion Institute, Pittsburgh.

Williams, S. T., and Gray, T. R. G. (1974). Decomposition of litter on the soil surface. *In* "Biology of Plant Litter Decomposition" (C. H. Dickinson and G. J. F. Pugh, Eds.), pp. 611–632. Academic Press, London.

Yi, S-C., and Kim, Y. C. (1996). Modeling of smoldering cellulosic materials—Evaporation and pyrolysis processes. *Preprints of the Division of Fuel Chemistry of the American Chemical Society* **41**, 1183–1186.

Yi, S-C., Bae, S. Y., and Kim, S. H. (1998). Heat transfer of a smoldering flammable substrate. Part 2. A theoretical model and its application. *J. Fire Sci.* **16**, 32–45.

Zasada, J. C., Norum, R. A., Van Veldhuizen, R. M., and Teutsch, C. E. (1983). Artificial regeneration of trees and tall shrubs in experimentally burned upland black spruce/feather moss stands in Alaska. *Can. J. For. Res.* **13**, 903–913.

Zech, W., Senesi, N., Guggenberger, G., Kaiser, K., Lehmann, J., Miano, T. M., Miltner, A., and Schroth, G. (1997). Factors controlling humification and mineralization of soil organic matter in the tropics. *Geoderma* 79, 117–161.