Forum: Issues, Management, Policy, and Opinions

Tree Injury and Mortality in Fires: Developing Process-Based Models

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ABSTRACT

Wildland fire managers are often required to predict tree injury and mortality when planning a prescribed burn or when considering wildfire management options; and, currently, statistical models based on post-fire observations are the only tools available for this purpose. Implicit in the derivation of statistical models is the assumption that they are strictly applicable only for the species or conditions for which they were developed. The result has been a profusion of separate models of uncertain generality. A parallel research effort, the process approach, has been directed at modeling tree injury and mortality by directly simulating the energy-transfer process from the fire to the exterior surface of the plant, and thence into roots, stems, and foliage. Process models can currently predict stem or tree death if certain injury thresholds are reached. We present a brief review of the current understanding of the biophysical processes causing fire-induced plant injury, and focus on the challenges associated with defining boundary conditions, initial conditions, and thermal and physical properties required for modeling plant heating and tissue necrosis. We argue for integration of statistical and process approaches to predicting tree injury and mortality wherein process models provide inputs for statistical models. Research gaps that hinder the application of process-based tree injury and mortality models include linkage of fire effects models with combustion models (especially coupled fire-atmosphere models) through the boundary conditions required for simulating tissue heating, descriptions of live tree thermal and physical characteristics, and better understanding of the physiological basis for delayed fire-caused mortality and the interactions between fire injury and second-order causes of mortality such as diseases and insects.

Keywords: boundary conditions, fire effects, plant mortality, process modeling, wildland fire

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INTRODUCTION

As a fire burns through a forest or shrub community, energy released in the combustion process can increase the temperature of the plant canopy, stem, and roots. If the heating is of sufficient magnitude and or duration, it can adversely affect the viability of plant tissues, impair plant function, and even kill the plant (Finney 1999, Dickinson and Johnson 2001, Michaletz and Johnson 2008). Visible effects of the heating such as charring of bark and stems are apparent immediately after the burn, followed by vascular cambium, bud, and leaf or needle necrosis. Plant mortality as a direct result of heating by the fire typically manifests within two to three years post fire (Ryan and Reinhardt 1988, Fowler and Sieg 2004, Hood *et al.* 2007), although recent work by Harrington (unpublished data) suggests that mortality in some species occurs over much longer periods. This kind of injury and the tree death that follows directly are hereafter termed first-order fire effects.

Ultimately, thermal injury initiates a cascade of physiological responses. Sub-lethal injury can cause increased susceptibility to adverse environmental conditions or ecological interactions such as herbivory, disease, or insect attack referred to as second-order effects (Waring and Pitman 1985). Other effects of fire on individual plants and their populations arise from changes to soil properties, nutrient cycling, light resource availability, seed bank availability, and erosion susceptibility (Trabaud 1994). Subsequent effects on local plant community development and forest growth unfold over decades and centuries (Ryan and Reinhardt 1988, Fowler and Sieg 2004).

Improvements in our ability to predict and understand long-term ecosystem and fire interactions requires improved tools for simulating short-term, first-order fire effects including plant injury and mortality. Fire-induced plant injury and mortality models can be grouped into two categories: 1) statistical models that involve regression equations relating injury and mortality to observable indicators, or 2) process models that explicitly simulate the underlying thermal and biophysical processes occurring when a plant is heated. Dimensional analysis of key physical variables and the statistical estimation of proportionality constants from plant injury data have also been used and represent a middle way between statistical and process approaches (c.f., Van Wagner 1973, Dickinson 2002, Bova and Dickinson 2005).

We discuss here: 1) limitations of statistical tree mortality models; 2) a historical overview of the development of process models; 3) the boundary conditions that drive root-, stem-, and crown-tissue heating; 4) initial conditions and thermophysical properties required by process models; 5) data requirements for applying process models to landscapes; and 6) the implications for fire effects modeling of developments in coupled fire-atmosphere modeling. We do not promote a particular numerical scheme nor do we discuss the mathematical derivation of process-based fire effects models as derivations are available from previous authors. We leave discussion of the process of tissue necrosis at elevated temperatures to Stephan *et al.* (2010). Soil heating processes are discussed more fully in Massman *et al.* (2010), although we do discuss boundary conditions for soil heating models here. Consideration of the physiological consequences of injury when fires do not kill trees outright is discussed elsewhere (see Kolb *et al.* 2007, Michaletz and Johnson 2008, Kavanagh *et al.* 2010). We conclude by highlighting gaps in understanding and modeling capabilities and the potential for synergy between statistical and process approaches.

STATISTICAL TREE MORTALITY MODELS

For nearly a century (e.g., Flint 1925, Starker 1934, McCarthy and Sims 1935), authors have constructed models for tree mortality based on tree characteristics (e.g., stem diameter, age, etc.) and readily observable fire impacts such as bole char and crown scorch for species primarily found in North America. Bevins (1980), Ryan *et al.* (1988), and Ryan and Reinhardt (1988) developed statistical correlations for tree mortality based on observable fire impacts such as crown injury, bole char, and ground char. McHugh and Kolb (2003) quantified tree mortality up to three years post-fire in ponderosa pine (*Pinus ponderosa* Lawson) forests of the southwestern US. They reported that bole char and crown injury were the best indicators of mortality. In hardwoods, stem bark char height was found to be an important indicator of the likelihood of mortality along with tree size and species (Regelbrugge and Smith 1994). Reviews of statistical models developed over the past few decades for predicting fire-induced mortality in ponderosa pine and Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) conclude that the statistical models can be relatively accurate (±20%) within the geographical bounds (c.f. Fowler and Sieg 2004, Sieg *et al.* 2006, Hood *et al*. 2007, Michaletz and Johnson 2008). However, Michaletz and Johnson (2007) argue that the way relations among variables are chosen for these models fundamentally obscures the processes by which trees die, leading to confusion about mechanisms and increases the need to develop a new model for each novel situation (c.f., Dickinson and Johnson 2004). Some work has been presented for species outside North America. For example, Fernandes *et al.* (2008) propose a fire resistance rating for European pine species based on the work by Peterson and Ryan (1986), and suggest that most empirical studies are based on low-intensity fires; therefore, it should not be assumed that their results will apply to high intensity fires. Gromtsev (2002) identifies a lack of such studies on species in Russia, and others (Bond 1983, Angelstam 1998) found similar paucity of studies and data for species found in South Africa. Regardless of the physical basis of their development, statistical models have emerged as the most widely used fire-induced plant mortality decision support tools (Hood *et al*. 2007), but it is the inherent lack of physical basis that limits their applicability across regions, species, and changing stand and climate conditions.

DEVELOPMENT OF PROCESS MODELS

In theory, a predictive system combining process models of plant injury, tree physiological response to injury, and fire behavior would be more widely applicable across species, sites, and climatic conditions than statistical models, and could provide increased capability for predicting fire-induced mortality before a fire occurs (Jones *et al.* 2004, and 2006, Michaletz and Johnson 2007). In addition, fire simulation tools linked with forest growth simulation tools (e.g., Keane *et al.* 1996, Reinhardt and Crookston 2003) show promise for exploring long term forest response to landscape fire regimes, including establishment of new ecosystem states that may favor more frequent fire (Bergeron 1991, Turner and Romme 1994, Finney 1999, Strom and Fulé 2007). Statistical models may have limited validity for use in simulating fire effects under future climate scenarios (e.g., Lenihan *et al.* 1998), whereas the more mechanistic the fire effects model, the more likely its predictions will be relevant under novel conditions.

Process models directly simulate energy and mass transport occurring during the heating event to determine thermal impact on the viability of living plant cells. Currently, plant injury process models cannot predict mortality where partial injury to the cambium or the population of crown meristems occurs (see Kavanagh *et al.* 2010). Instead, mortality is predicted when cambium necrosis occurs around the circumference of the stem, or all crown bud meristems are killed (Michaletz and Johnson 2008).

Figure 1 presents a conceptual schematic depicting theoretical links between fire behavior prediction mechanisms and processes governing tissue heating, injury and, ultimately, reduced plant growth efficiency and mortality based on direct simulation of the primary biophysical and thermodynamic processes occurring during the fire event (Dickinson and Johnson 2001, Butler 2004, Michaletz and Johnson 2008).

All process models require assumptions about the geometry of the plant system and dimensionality of the mathematical models. One possible approach to the geometry is to approximate roots, stems, needles and branches as cylinders; buds, seed pods, and cones as spheres; and leaves as disks. Because the most accurate approach would simulate energy and mass transfer in three dimensions, reduced dimensionality is more practical and desirable from a computing perspective. Cylindrical components representing roots, stems, and branches are typically sectioned into concentric zones approximating the bark, cambium, and sapwood. Each zone may be defined by unique physical, thermal, and biological properties.

Soil and Root Heating

Duff combustion and attendant long-term basal heating, fine root consumption, and soil heating have been shown to be important for mortality of old-growth trees in fire suppressed stands with basal duff accumulations (e.g., Ryan and Frandsen 1991, Swezy and Agee 1991, Varner *et al.* 2005), but the effects of duff consumption appear to be species and site specific and more significant where roots are

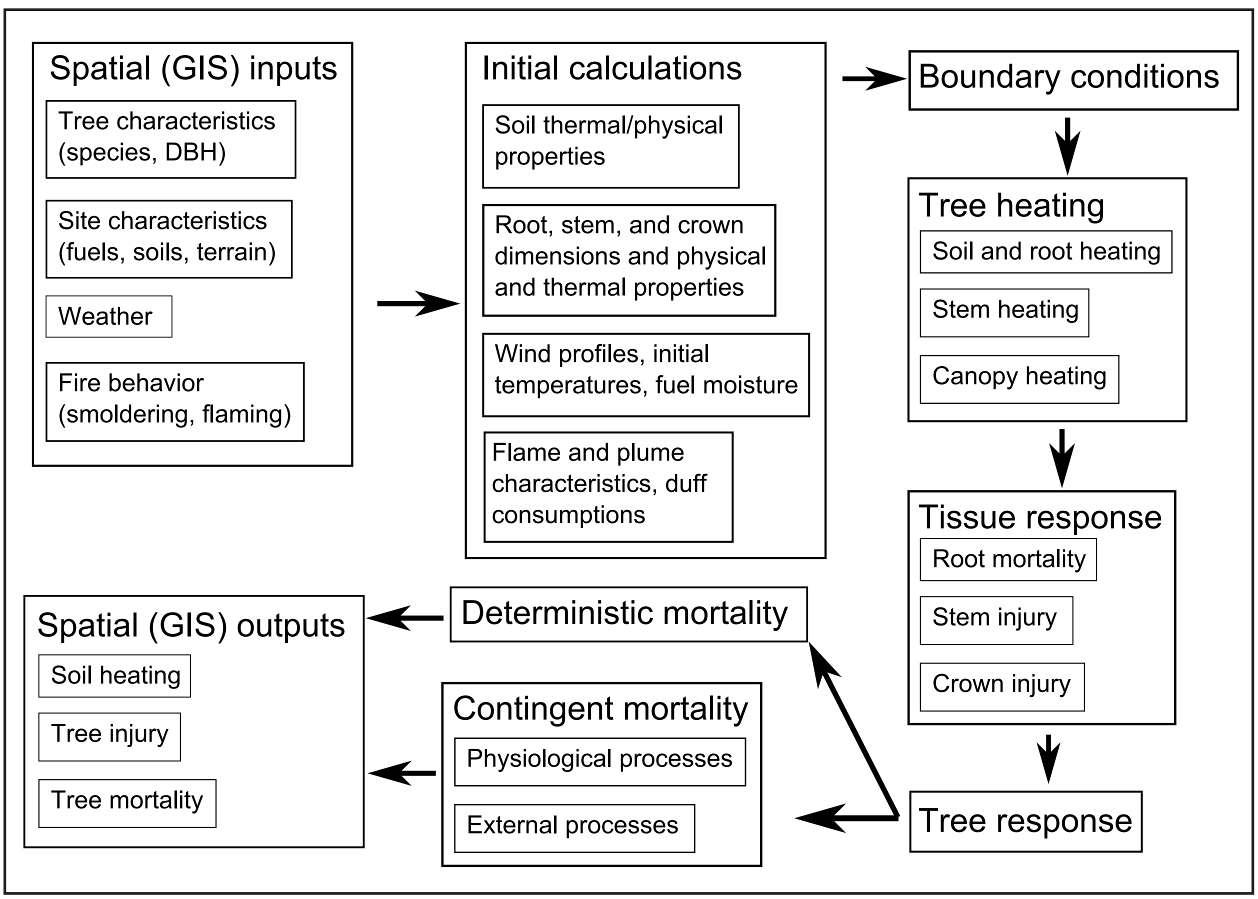

Figure 1. A conceptual diagram of the sequential linkages between the physical and biological processes contributing to fire-induced tree mortality.

concentrated close to the soil surface and growing in the duff itself (Kolb *et al.* 2007). Apart from its direct effects on roots and stem bases, duff consumption also has other important ecological effects. For example, duff consumption is a major determinant of the spatial pattern of erosion potential, seedling establishment, tree regeneration, and herbaceous diversity after fires (Miyanishi and Johnson 2002, Certini 2005, Massman *et al.* 2010).

No explicit model of root heating has been developed. Steward *et al.* (1990) used a 60 °C threshold to indicate where root necrosis would occur in soils as a function of surface heat flux from combustion. Hungerford *et al.* (1991) and Ryan (2002) provide temperature thresholds for a variety of soil effects arising from fire-induced heating (see also Massman *et al.* 2010). Stephens and Finney (2002) included a duff reduction variable in their mortality models while others (Ryan and Amman 1994, McHugh and Kolb 2003) observed significant differences in the magnitude of ground char between live and dead trees but did not find that variability to be statistically significant in their multivariate models. However, very few studies focus on how roots are affected by long term, moderately elevated temperatures, such as often occur during smoldering duff combustion.

Stem Heating and Injury

Early efforts to develop process models of stem injury focused on analytical solutions of the heat conduction model for transient heat exposures (Spalt and Reifsnyder 1962; Martin 1963*a*, 1963*b*; Vines 1968; Dickinson and Johnson 2004). Conduction models were later applied numerically to allow for more realistic time-varying surface heating. Rego and Rigolot (1990) employed a one-dimensional Taylor-Series numerical solution to describe heat transfer through a plant stem. The stem was approximated as a flat semi-infinite slab composed of three layers (bark, cambium and sapwood). Predicted cambium temperature-time curves showed a slightly slower time response than the actual data. Costa *et al.* (1990) employed a two-dimensional control volume approach, treating the stem as an infinite cylinder. Their predicted cambium temperatures showed a faster response to external heating than their measurements.

Jones *et al.* (2004 and 2006) formulated a numerical thermal transport model and used it to predict cambial necrosis on four tree species. Their work identified the importance of temperature and moisture dependence of thermal properties and suggested that desiccation, devolatilization, charring (Gill and Ashton 1968), and thermally induced swelling of the bark (Butler *et al.* 2005) are critical to accurate modeling of cambium temperature histories (Kayll 1963, Hare 1965).

The energy incident on the exterior surface of plant components typically varies through both time and space. For example, the energy incident on the stem is not uniform around or along it, implying that any process model must simulate energy transfer as a function of time and, at least, radial location. Jones *et al.* (2004, 2006) showed that for stems greater than 4 cm in diameter, a one-dimensional model could be applied at multiple locations around the stem to approximate multidimensional heat transfer, providing that the number of nodes used in the numerical discretization scheme was high enough to obtain a grid-independent solution.

Along with the development of process models came the realization of, and focus on, the related need for improved understanding of how heating affected cambial cell necrosis. Martin (1963*a*) first showed how the temperature-dependent rate processes by which fire injury occurs could be applied to cambium necrosis and tree mortality. Jones *et al.* (2006) and Dickinson and Johnson (2004) implemented thermal tolerance models in their stem heating simulations. Multispecies comparisons of thermal tolerance (Lorenz 1939, Dickinson and Johnson 2004, Jones *et al* 2004) confirm the overarching importance of bark thickness as the primary determinant of differences among species and stems of different sizes in vascular cambium necrosis.

Canopy Injury

Until recently, less attention has been paid to process modeling of canopy injury from fire than stem injury (see reviews in Dickinson and Johnson 2001, Michaletz and Johnson 2007). Van Wagner (1973) used a plume model that described maximum gas temperatures at height and, under the assumption that foliage temperature would approximate plume temperature, provided an accurate description of leaf scorch data from field experiments. Michaletz and Johnson (2006*a*) extended Van Wagner's work, arguing that the energy transfer in small diameter crown and root components (nominally less than 1 cm in diameter) could be approximated using the "lumped capacitance" solution. Conversely, Frankman *et al.* (2010) directly modeled the thermal gradients in small woody particles and concluded that a lumped capacitance approach is not valid in most cases of energy transfer in small stems, needles, leaves, and buds. Mercer *et al.* (1994) considered vulnerability of aerial seed banks to heating in plumes during fires. The fruits in which the seeds were contained exhibited significant temperature gradients during heating. Clearly, additional research is warranted.

Kavanagh *et al.* (2010) hypothesize that necrosis from heat is not the only relevant effect of forest fire plumes. Vapor pressure deficits (VPDs) in the plume appear to be sufficient to cause disruption of foliage and branch function well above the heights at which foliage necrosis from heat is predicted. The potential physiological consequences of large VPDs in the plume cast doubt on the assumption that crown scorch is generally the result of heat-induced tissue necrosis.

Integrating Root, Stem, and Crown Injury

Michaletz and Johnson (2008) used a biophysical process approach to describe the combined effects of stem and canopy bud necrosis, predicting tree death if 100 % of the stem was girdled or 100 % of the canopy buds were killed by heating. No other integration of root, stem, and canopy injury has been conducted to our knowledge. Further research exploring the physiological effect of injury below the level at which stem death is deterministic is needed (see Kavanagh *et al.* 2010).

BOUNDARY CONDITIONS

A key requirement for linking fire behavior with tissue heating and injury is a description of the heat flux or temperature regime at the surface of roots, stems, and canopy elements—in other words, a description of the boundary conditions for heating. Typically, an adiabatic or symmetric boundary condition is applied at the interior or central axis of plant components, while a time history of surface temperature or surface heat flux is required for the exterior boundary condition.

It is well documented that energy fluxes in wildland fires vary widely over time (Wotton *et al.* 1998, Butler *et al.* 2004, Frankman *et al.* 2010). A typical time course of temperatures at the bark surface and cambium is shown in Figure 2. The data indicate that heating from flames is transient, although heating from duff and woody fuel consumption may be sufficiently long-term and consistent that steady-state approaches are possible (Frandsen 1989). So, while in a few cases a steady-state energy transport model may be acceptable, in general all solutions should be based on a transient calculation where surface temperature or surface heat flux can vary over time.

Two options exist for defining the exterior boundary condition: 1) a surface temperature history, or 2) a specified surface incident heat flux history (conductive, radiant, convective,

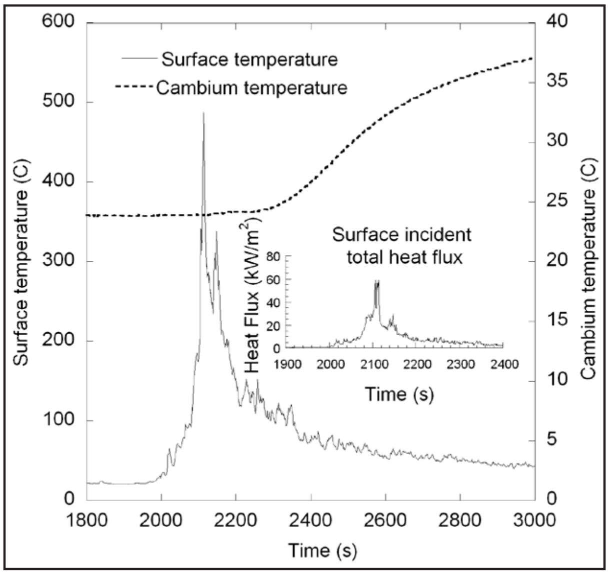

Figure 2. Surface heat flux and resulting measured surface and cambium temperatures for a 28 cm diameter (dbh) lodge pole pine subjected to a prescribed crown fire.

or any combination of the three). From the viewpoint of computational complexity, the two types of boundary conditions are essentially equal. The difference is in how the boundary condition data are acquired. Stem heating models like those of Costa *et al.* (1990), Rego and Rigolot (1990), and others have assumed that the bark surface temperature can be approximated from knowledge of flame residence time and flame temperature (e.g., Gutsell and Johnson 1996, Dickinson and Johnson 2004). Canopy effects models have used measurement (e.g., Mercer *et al.* 1994) and plume models to supply the exterior boundary conditions (e.g., Van Wagner 1973, Michaletz and Johnson 2008, Kavanagh *et al.* 2010). The heat flux boundary condition has been used sparingly in models of fire-induced plant injury, possibly because of a perceived increase in model complexity, but more likely due to the lack of published heat flux data (Vines 1968, Jones *et al.* 2004).

The temperature boundary condition does not necessarily provide an advantage when linking mortality models with fire behavior prediction models. Measuring and recording surface temperatures is relatively straightforward; however, the uncertainties associated with these measurements can be significant (Shaddix 1999, Kremens *et al.* 2010). The stem surface temperature is a complex function of the surface structure; the surface radiative properties, the thermal status (temperature and emissivity) of the surrounding environment; and the location, size, and thermal intensity of the source term (i.e., fire).

Typically, heat flux incident on the surface of a cylindrical component is obtained either from direct measurement or from a fire behavior model. The dominant modes of energy transfer in stem and crown heating are radiation and convection (Jones 2003, Bova and Dickinson 2009). Jones *et al.* (2004) showed that the actual energy absorbed into the plant component depends on complex thermophysical properties and relations governing the three modes of energy transfer (conduction, convection, and radiation). As discussed in Kremens *et al.* (2010) and Jones (2003), estimating radiative and convective flux to objects in fires is a two-fold problem involving heat release from the fire and its reception at a surface (e.g., bark surface) at some distance from the moving fire front (Bova and Dickinson 2009, Frankman *et al.* 2010). Estimating radiative heat flux requires knowledge of radiative emittance from the flames and its absorption at the surface of interest (e.g., a stem). Radiative energy transfer depends on properties that can be spectrally and temperature dependent such as emissivity, absorptivity, surface temperature, and surface roughness. Generally, the required spectral and thermophysical properties are not currently determined. Convective energy transfer is governed by interactions between many of the same properties as well as local flow intensity, surface and air temperatures, and surface roughness.

For purposes of linking post-fire effects with fire behavior models, heat flux must be calculated from inputs provided by a fire behavior model (see also Kremens *et al.* [2010] for discussion of other measurement issues). Heat flux is also a logical output from fire behavior models. Measuring bark surface temperatures accurately is not as straightforward as is often assumed; therefore, surface heat flux seems to be the more practical boundary condition. Kremens *et al.* (2010) and Bova and Dickinson (2009) present a general discussion of temperature measurement.

If a heat flux boundary condition is used, net heat flux (incident flux minus outward-bound heat losses from the surface) must be calculated (e.g., Bova and Dickinson 2009). Estimates of incident flux can be obtained from models or measurement, though measurements may often need correction (e.g., Schneller and Frandsen 1998, Jones *et al.* 2004, Frankman *et al.* 2010). Wavelength dependence of devices used to estimate incident radiative flux must also be considered (Kremens *et al.* 2010). Models of radiative and convective heat transfer to instruments (Knight and Sullivan 2004), fuel elements (Larini *et al.* 1998, Frankman *et al.* 2010), and thermocouple probes (Bova and Dickinson 2005) have been developed and could be modified to provide the link between current operational fire models and plant heating.

Boundary Conditions for Root and Stem Basal Heating

The primary uncertainty in predicting soil heating lies in the boundary conditions. Soil heating occurs through energy transport by conduction, advection, and radiation through the interstitial spaces and solid materials of the forest floor layers and soil. All depend strongly on the transport of moisture ahead of the thermal front (Schneller and Frandsen 1998, see Massman *et al.* 2010).

Duff can either insulate or heat the soil, depending on whether it is consumed. Bradstock and Auld (1995) found that soil heating was more related to fuel consumption than fireline intensity in low consumption bushfires (≤2 kg m^{-2}), explaining why soil heating resulting from rapidly spreading, low consumption surface fires has generally proven to be inconsequential (e.g., Viegas *et al.* 2000). Palmer (1957), and later Hawkes (1993), report measurements that indicate that a critical minimum duff layer depth exists, below which heat loss exceeds heat generated by combustion, implying that for a layer with thickness less than the minimum depth, no sustained combustion will occur and, consequently, the duff is primarily a soil insulator. Valette *et al.* (1994) report that when the ground surface is exposed to low- to moderate-intensity heating (<100 kW m^{-2}), unconsumed duff layers reduce maximum soil temperatures by as much as an order of magnitude. Van Wagner (1972) related duff consumption to downward radiation from the flame front, which implies that, in systems with intense fires and thin duff, duff consumption during the flaming phase may contribute to soil heating. Including root heating in tree mortality models would likely be most important where there was long-term duff consumption or where patchy accumulations of woody fuel result in long-term soil surface heating (see Stephan *et al*. 2010). In systems with deep duff, smoldering independent of the flaming front will be the key cause of soil heating (Miyanishi and Johnson 2002). Relatively little is known about duff as an energy source for soil heating, so boundary conditions will have to be obtained from future experiment and modeling that incorporate the effects of duff depth and moisture.

Odion and Davis (2000) have shown that consumption of woody fuel accumulations can result in significant soil heating, implying that models for fuel consumption, moisture content, and woody fuel combustion are required (e.g., Albini and Reinhardt 1997, Brown *et al.* 2003). Meyer (2009) measured soil temperatures below small burning piles of woody debris. Temperatures in the ash layer on the soil surface exceeded 300 °C, but maximum temperatures 2 cm to 4 cm below the surface varied from 100 °C to 155 °C at the pile center, and from 35 °C to 120 °C at the pile edge. Massman *et al.* (2010) report more significant soil heating and gas advection below a large burn pile.

Some effort has focused on the development of models for predicting energy release during duff combustion. The First Order Fire Effects Model (FOFEM) uses the heat generated from duff consumption to provide boundary conditions, although the particulars are not specified (Reinhardt 2003). The fuel consumption software system CONSUME (Ottmar *et al.* 1993) uses a series of equations of physically-based form that are parameterized with extensive field measurements from key ecosystems, and could presumably be adapted to provide boundary conditions for soil heating models. Process-based models have been developed for smoldering combustion scenarios outside of wildland fire (c.f., Drysdale 1985). Smoldering combustion in industrial and building fires is largely limited by oxygen availability and energy loss, and models are typically one dimensional (Drysdale 1985, Miyanishi 2001, Dodd *et al*. 2009, Rein 2009). In a wildland fire application where ignition occurs at the upper surface of the duff layer, oxygen diffusion is not limiting; rather, energy loss due to heat of vaporization of moisture is the most critical factor (Miyanishi and Johnson 2002, Rein 2009). A first step in providing boundary conditions for soil heating would likely involve adaptation of these existing models (Miyanishi and Johnson 2002).

A duff moisture prediction system is needed to provide inputs to any future duff consumption model. Currently, there is no duff moisture model (either aspatial or spatially explicit) available for use by fire managers in the US. The Canadian Forest Fire Weather Index System includes a duff moisture code (Van Wagner 1987), but provides an average index of duff moisture that is not sufficiently process-based to be tailored to varying conditions. Interception of precipitation by tree canopies has been shown to cause greater duff consumption under tree canopies (Miyanishi and Johnson 2002, Hille and Stephens 2005). Consequently, process-based duff consumption models should consider spatially explicit drying and wetting processes. A promising process-based fuel moisture model exists that simulates the coupled heat and water budget of layered soil, duff, and litter, and can be run with currently available meteorological inputs (Matthews 2006, Matthews *et al.* 2007).

Over the long term, process-based duff consumption models would be expected to provide a point of comparison for CONSUME (Ottmar *et al.* 1993) and would have greater potential to provide predictions where field measurements have not been conducted. Rein (2009) indicates that the severe lack of published thermophysical properties of materials constituting duff layers is an impediment to future process-based duff combustion modeling.

Boundary Conditions for Stem Heating

Tree stem heating is caused by convective and radiative heat transfer from a spreading flaming front (Jones *et al.* 2004, Bova and Dickinson 2005). Measurements on the side of trees facing oncoming fires show that integrated heat flux at the stem surface (kJ m^{-2}) correlates with fireline intensity (kW m^{-1}) and, in turn, tissue necrosis depth (Bova and Dickinson 2005). Conduction, determined by the thermal diffusivity of bark and underlying wood, is the dominant heat transfer mode in stem heating during fires, and bark thickness is a key determinant of the temperatures reached at the cambium in response to fire exposure (e.g., Spalt and Reifsnyder 1962, Martin 1963*a*, and Vines 1968).

Plant bark surfaces can vary from relatively smooth to deeply fissured with intervening flat plates. Kayll (1963) showed that when heat was applied to fissured bark, much higher surface temperatures occurred on the plates than in the fissures. It was reasoned that because thick outer bark provides more insulation, the rate of heat transfer to the cambium may be roughly the same through both plates and fissures, suggesting that, while the exterior surfaces of some plant stems are relatively rough, smooth surfaced models may be an acceptable approximation (Jones *et al.* 2004). Clearly, further measurements and study are needed.

Measurements and models separating radiant and convective components and the interaction between flames and stems are needed for characterizing boundary conditions for stem heating. Studies that attempt to separate the heat-transfer mechanisms governing fire propagation can contribute to efforts to obtain boundary conditions (e.g., Anderson 1964, McCarter and Broido 1965, Fang and Steward 1969) as well as studies focusing on convection (Scesa and Sauer 1954, Lee and Emmons 1961, Prahl and Tien 1973, Wolff *et al.* 1991) and or radiation (Depuy 2000, Morandini *et al.* 2002) as mechanisms of flame propagation.

In surface fires where Reynolds numbers are high enough (i.e., where either gas velocities or stem diameters or both are large enough) that the interaction between flames and stems results in eddying and standing leeward flames, stem surface heat flux is uneven, both around the stem and vertically, creating leeward charring patterns and fire scars that are widest near the ground and taper up the stem (e.g., Gutsell and Johnson 1996, Inoue 1999). To date, field measurements of uneven heating of tree stems have focused on oncoming fires burning over flat ground (Gill 1974, Fahnestock and Hare 1964, Inoue 1999). Only one measurement of circumferential heat flux has been made, documenting the elevated heat fluxes that occur on the uphill sides of stems caused by slope-induced buoyant flow during fires, whether backing or heading (Bova and Dickinson 2009).

Generally, it has been assumed that advective energy transport due to the movement of water and nutrients up and down the plant stem is relatively slow and therefore negligible. However, there is logic suggesting that for trees that are actively transpiring during fire, a fully three-dimensional solution is required because vertical transport of energy along the axis of the cylinder significantly affects local cambium temperatures (Vines 1968, Ryan and Frandsen 1991, Kavanagh *et al.* 2010). Measurements are required to confirm that heat transport by this mechanism is of sufficient magnitude to warrant inclusion in models.

Boundary Conditions for Canopy Heating

Despain (2004) suggests that energy release rates and associated temperatures are sufficiently high in actively burning crown fires to kill all small diameter (e.g., >0.5 cm) branches, needles, leaves, and buds. As such, consideration of the plume rising above surface fires will generally be of most interest to canopy-injury modeling. Current models simulating the heating of foliage require average or maximum plume temperatures. For modeling heat transfer to buds, branches, and fruits, plume residence times, gas velocities, and, as discussed in the foregoing, VPDs are also needed.

A range of models have been used to provide boundary conditions for canopy-effects modeling. At the most basic level, Van Wagner (1973) used field data (fireline intensity and foliage necrosis height) and a plume model providing maximum plume temperatures to estimate the proportionality constant for a model that predicts the height of foliage necrosis. Van Wagner's (1973) approach is based on the assumption that foliage temperatures closely track plume temperatures (i.e., that convection is highly efficient) and has been the basis for subsequent "crown scorch" models. Mercer *et al.* (1994) in their work on the heating of fruits in plumes, used a time-varying fruit surface temperature as the boundary condition for a numerical conduction model. An integral plume model (Mercer *et al.* 1994) has been adapted to provide not only plume temperatures, but also gas velocities and plume gas composition, and used to explore faunal exposures (Dickinson *et al.,* unpublished data) and the effects of plume vapor pressure deficits on modeled embolism in conifer branches (see Kavanagh *et al.* 2010).

Complicating the description of boundary conditions for modeling the heating of canopy elements for many species is the shielding of buds and branches by foliage (Michaletz and Johnson 2006*a*, 2006*b*). Pickett *et al.* (2009) have demonstrated a sheltering effect that effectively reduces the combustion temperature and burning rate of a single leaf when placed above a similar leaf in a vertically rising hot buoyant plume.

Coupled fire-atmosphere models show promise for exploring canopy heating where a line-source plume model (e.g., Mercer *et al.* 1994, Kavanagh *et al.* 2010) is clearly not appropriate. One such area is where multiple point ignitions are used in prescribed fire operations and high densities of ignitions result in high mortality rates from canopy effects (M. Bowden, Ohio Division of Forestry, personal communication). The point ignition densities at which high mortality rates were observed were higher than those described in Johansen (1984), where no effect of density on canopy injury was observed. It is not clear whether the greater effects on trees from dense arrays of point ignitions were related to merging firelines or the existence of an area source of heat rather than a line source. A general structural fire model was recently used to simulate plume behavior and compared favorably with experimental data (Sun *et al.* 2006). Field data for plume model validation are sparse (see Kremens *et al.* 2010).

INITIAL CONDITIONS AND THERMOPHYSICAL PROPERTIES

Before a solution can be calculated, initial values must be defined for the temperature and other properties of the root, canopy, or stem. Intuitively it is recognized that tree stem temperature profiles (and likely moisture distribution) follow a diurnal cycle, lagging in phase and amplitude behind the surface temperatures and are a function of the ambient temperature and environment, as do the heat transfer properties of the stem, root, or canopy element (Kapur and Narayanamurti 1934, Reynolds 1939, Koljo 1948, Aichele 1950). Although the simplest approach is to assume a fixed initial temperature profile, a more accurate method might be to follow the work of Jones *et al.* (2004) and Potter and Andresen (2002) and directly model the daily temperature cycle within a tree as a function of solar insolation and ambient conditions to acquire the initial temperature profile within the plant component for the fire injury calculation. Additional measurements of diurnal fluctuations in plant component temperatures are needed to clarify the magnitude of these temperature cycles and their impact on cambial heating.

For roots, stems, and branches, the geometrical representation can either be approximated by multiple concentric layers (i.e., bark, cambium, sapwood), where the properties within each layer are considered constant, or by a continuous function. Following the concentric layer representation of a stem or branch, the innermost layer of the cylinder is wood, with sapwood being the layer closest to the cambium. Moving outward, the next layer is the cambium, which is thin, being one to a few cells thick. Inner bark comes next with its thermal properties dominated by high moisture content. The outer, or fourth, layer is the outer bark characterized by significant variability among species in density and thermal properties.

The density, moisture content, and other properties can vary significantly between each successive layer within the same tree (Figure 3). Most published thermophysical data have been developed for wood as a structural material and, thus, are for constant temperature and relatively low moisture conditions (Simpson and TenWolde 1999). When considering thermal transport in living or dead woody compo-

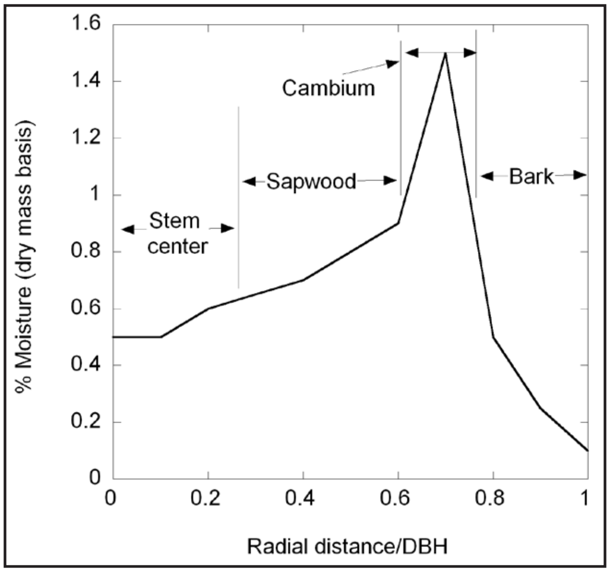

Figure 3. Moisture distribution (dry mass basis) and oven dried density as a function of radial location in a 45 cm diameter ponderosa pine stem.

nents typical of forest environments, the critical thermal properties can be strongly dependent on the temperature and the moisture content and can vary significantly between species (Stamm 1964, Jones *et al.* 2004). Several studies (e.g., Millikin 1955, Martin 1960, Spalt and Reifsnyder 1962, Martin 1963*b*, Reifsnyder *et al.* 1967, Lamb and Marden 1968, Martin and Crist 1968) report physical properties such as thickness, density, moisture content, thermal conductivity, heat capacity, moisture absorption, and desorption rates for wood and bark of a few species over a limited range of moisture contents. Jones *et al.* (2004) assumed that at least some moisture is bound either chemically or through physiological processes and is not freely transported by heating and evaporation, and postulated that the latent heat of vaporization of water protected the cambial tissues by slowing the advancing energy waves. Clearly, additional measurements and characterization of the thermal properties of stem and root components as a function of species, temperature, and moisture content are needed.

Some work has focused on the transport of moisture through dead wood (Siau *et al.* 1986; Skaar 1988; Nelson 1989, 1992). It is generally held that the primary effect of moisture is to limit the bark temperature rise at some value near the boiling point (e.g., Byram *et al.* 1952). Lee and Diehl (1981) measured the temperatures of oak dowels of varying moisture contents as they were heated from room temperature to ignition. The internal temperature of the high moisture-content dowels climbed at a constant rate up to 100 °C, leveled off briefly (while the moisture presumably evaporated), then continued upward at a new, steeper rate. In experiments on live leaf samples, Pickett *et al.* (2009) found that 30 % to 60 % moisture (dry mass basis) remained in the sample at ignition and that the leaf temperature rise paused at 200 °C to 300 °C rather than at 100 °C, suggesting that models of thermal response based on the behavior of dead wood samples may not apply to live fuels. Further research is needed to fully determine the impact of moisture on heating of live plant components.

Applying process-based fire effects models requires description of a variety of tree characteristics that is allometrically related to tree size. For modeling stem injury, bark thickness is required and is a species-specific function of tree size (e.g., Uhl and Kauffman 1990, Hengst and Dawson 1994, Jackson *et al.* 1999). Vertical distribution of foliage, bud, and branch populations within a crown are also species-specific functions of tree size and growth environment. For instance, Ackerly and Donoghue (1998) described two suites of co-evolving traits among 17 species of maples. The first suite of positively correlated traits were twig thickness, leaf size, inflorescence length, and branch spacing, while the second suite was crown size, stem diameter, and total leaf area. In their model integrating fire-caused stem and crown injury, Michaletz and Johnson (2008) described vertical bud distributions as a function of stem diameter and the vertical taper of sapwood. Predicting the extent of injury to root systems will also require descriptions of rooting patterns that will be specific to ecosystems (e.g., Jackson *et al.* 1996, Schenk and Jackson 2003), tree functional group (Jackson *et al.* 1995), and size (e.g., Niklas 1992, West *et al.* 1999).

LANDSCAPE-SCALE DATA FOR FIRE EFFECTS MODELS

Both in North America and elsewhere, there is an increased emphasis on fire management over fire suppression; thus, it will be important to develop the ability to predict when and under what conditions wildfires will result in resource benefit or harm (Fire Executive Council 2009)—a determination that requires answers at a landscape scale. The First Order Fire Effects Model (see Reinhardt and Dickinson 2010) is used in a range of software systems to provide spatial information on fire effects, and many of the process model advancements we've discussed have relevance for the continued improvement in FOFEM. Fire effects modeling has the potential to contribute more than it currently does to the wildfire decision-making process, particularly in the context of the Wildland Fire Decision Support System (WFDSS) that was designed to support the new US wildland fire policy (Fire Executive Council 2009), but development of the spatial inputs to both fire and fire effects models are required, along with validation datasets.

Validation of fire effects model accuracy at landscape scales is key to developing managers' confidence that such models can be effective tools in selecting optimum management options prior to, during, and after fire (see also Kremens *et al.* 2010). Current operational fire models (Rothermel 1972, Finney 1998, Stratton 2006) have proven to be invaluable as decision support tools for fire management, but they have many weaknesses (e.g., they do not output energy flux, nor do they incorporate a full description of vegetation variability). Weaknesses in fire effects prediction will follow from weaknesses in fire behavior prediction. Landscape-scale predictions of fire intensity are fraught with uncertainty due to the dependence of fire on spatially and temporally varying environmental and ecological factors (Agee and Huff 1980; Don Despain, National Park Service, unpublished report; Turner and Romme 1994; Bessie and Johnson 1995; Finney 1998, 1999; Gardner *et al.* 1999). Spatial variability in vegetation type and structure, fuel moisture and weather predictions, and simplifications inherent in currently used fire models are the most serious limiting factors for spatially resolved fire modeling (both smoldering and flaming) and apply equally to fire effects prediction (van Mantgem *et al.* 2001). Clearly, improved fire models are critical to process-based fire effects models.

Improvements in duff consumption modeling would improve soil heating and root injury predictions, as well as smoke transport modeling, but will require landscape maps of duff characteristics as well as a high spatial resolution duff moisture model that is sensitive to hydrological and vegetation characteristics. Fire effects prediction at landscape scales requires inputs above and beyond the inputs required for duff consumption and fire spread models currently used in fire operations. Soil heating models require soil characteristics (Massman *et al*. 2010), and tree injury and mortality models require a range of information specific to tree species and size (see Kavanagh *et al*. 2010). Clearly, a focused effort to obtain species-specific and ecosystem-specific information on thermophysical properties, the allometry of tree root and shoot systems, and forest species composition and tree size structure will be required for fire effects process models to be implemented on a landscape scale.

Given that fire behavior and other initial conditions and process-model parameter values were available, it would be possible to use a combination of currently available process and statistical fire effects models to generate a composite burn index (Key and Benson 2005, Key 2006) that could be compared with maps generated from remotely sensed data (e.g., Cocke *et al.* 2005, Wimberly and Rielly 2007). However, it has not been possible to use Landsat to discriminate among vegetation layers (e.g., understory, midstory, and canopy) in fire effects because the reflectance from a given pixel is integrated across all vegetation layers; thus, the only possible target for validation is some composite effect (Kremens *et al.* 2010).

COUPLED FIRE-ATMOSPHERE PROCESSES

Atmospheric stability and moisture distribution in the atmospheric layers above the surface boundary layer can significantly influence fire behavior (Clark *et al.* 1996, Potter 2002, Linn and Cunningham 2005, Heilman and Bian 2007). For example, wind turbulence can contribute to an already unstable atmosphere to enhance wind flow fluctuations near the ground that can cause rapid changes in fire intensity and spread direction. Mughal *et al.* (2007) indicate that low level winds can be induced by the fire plume and that these winds can then result in a positive feedback loop, essentially further increasing the fire's intensity. Clark *et al.* (1996) indicate that, as fireline length increases, individual plumes are formed, and the interaction between these plumes can lead to highly variable surface winds that influence fire intensity and growth. Charney and Fusina (2006) suggest that vapor pressure deficit in the boundary layer is associated with changes in fire intensity. While most physics-based fire models do not formally couple the atmosphere and the fire, a few such models have been presented (Mell *et al*. 2007). Coupled fire-atmosphere models (e.g., Coen 2005, Linn and Cunningham 2005, Sun *et al.* 2009) have the potential to contribute substantially to fire effects modeling. Fluxes of mass, momentum, and energy are explicitly modeled and can be used to estimate the boundary conditions for process-based fire effects models. Though coupled fire-atmosphere models are not currently designed to provide real-time forecasts, they have the potential to provide the boundary conditions that link outputs from landscape fire models (models that are used operationally) with process-based fire effects models. In addition, coupled fire-atmosphere models provide an opportunity to define the limitations of current fire models.

We would expect coupled fire-atmosphere processes to increase the predicted variability in fire behavior over that derived from non-coupled models when fires burn with complex spread patterns on realistic terrain. Coupled fire-atmosphere processes confirm that temporal and spatial variability is an inherent feature of fire behavior (Sun *et al.* 2009), which, ultimately, will translate into uncertainty in fire effects predictions.

Although they are not yet ready for operational use at landscape scales, coupled fire-atmosphere models have potential for near- to medium-term application in fire effects modeling. Coupled fire-atmosphere models are currently being used to simulate fire and plume behavior at small spatial scales to provide flame and plume characteristics needed for calculating boundary conditions for fire effects models (Bova and Dickinson, unpublished data; Michaletz and Johnson, unpublished data). Coupled fire-atmosphere models can be used to produce look-up tables of fire and plume characteristics from multiple simulations over relevant ranges in fuel, weather, and topographical conditions.

CONCLUSIONS AND RESEARCH OPPORTUNITIES

Ultimately, linking fire behavior, plant injury, and plant physiological process models offers a way forward for both the merging of statistical and process approaches and development of a comprehensive tree mortality prediction system. A handful of studies have considered the physiological consequences of injury caused by fires (e.g., Ryan 1993, Kolb *et al*. 2007, Michaletz and Johnson 2008, Kavanagh *et al*. 2010). A few attempts at developing process models to predict crown scorch, crown consumption, bole injury, surface fuel consumption, and root necrosis have been presented, but understanding and modeling of the physiological responses to injury are not sufficiently developed to support process models that would predict mortality from sub-lethal levels of injury. Process models could provide tree injury input (e.g., root necrosis, stem vascular cambium necrosis, and necrosis of canopy elements) to statistical tree mortality models. At the very least, as their development proceeds, process models will be valuable as a point of comparison with statistical tree mortality models, perhaps in the sense of ensemble forecasting. Ensemble forecasts with multiple models are used in meteorology (e.g., Goerss 2000) and, thus, there is good precedent for this approach. With fire policy throughout the world evolving toward greater use of fire management, fire effects forecasts based on multiple models could be a valuable source of information when considering various management strategies. Basing statistical models on independent variables that could be predicted by process models would make extrapolation of the statistical models to novel species and conditions (e.g., a changed climate) scientifically more defensible.

Several gaps in our understanding must be addressed before fully operational and comprehensive process-based models simulating soil, stem, and canopy heating can be developed. Stem heating models could provide adequate predictions of cambium necrosis, but how bark and sapwood moisture affect cambium temperature distributions is poorly known. Canopy injury models require plume characteristics, yet plume models are poorly validated. No clear consensus has yet emerged regarding the most appropriate approach to modeling energy transport in small-diameter stems, leaves, and needles. Obtaining reliable boundary conditions for soil heating may be the greatest challenge, given the need for spatially explicit duff moisture and duff smoldering predictions. The database of species-specific thermophysical properties must be expanded as well as our ability to describe tree geometry (i.e., root, branch, leaf, and needle geometry, spatial distribution, and physiology) based on tree age, species, and ecosystem. Only with advances in our ability to model tree physiological response can we integrate site factors such as drought history, forest stand age, stand density, insect populations, and soil productivity into process-based fire effects predictions.

Applying fire effects models at landscape scales, both in an operational forecasting mode and as a part of ecosystem simulations under current and future climate, is an area of opportunity, but will require substantially improved capabilities for predicting spatial variations in fire behavior (smoldering and flaming) as a function of spatially varying initial conditions (e.g., forest characteristics). New developments in basic fire behavior modeling and models that simulate coupled fire-atmosphere processes show the potential for improved ability to predict fire behavior locally and over large extents. Such models are already providing boundary conditions for fire effects models.

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