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Linking 3D spatial models of fuels and fire: Effects of spatial heterogeneity on fire behavior

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A B S T R A C T

Crown fire endangers fire fighters and can have severe ecological consequences. Prediction of fire behavior in tree crowns is essential to informed decisions in fire management. Current methods used in fire management do not address variability in crown fuels. New mechanistic physics-based fire models address convective heat transfer with computational fluid dynamics (CFD) and can be used to model fire in heterogeneous crown fuels. However, the potential impacts of variability in crown fuels on fire behavior have not yet been explored. In this study we describe a new model, FUEL3D, which incorporates the pipe model theory (PMT) and a simple 3D recursive branching approach to model the distribution of fuel within individual tree crowns. FUEL3D uses forest inventory data as inputs, and stochastically retains geometric variability observed in field data. We investigate the effects of crown fuel heterogeneity on fire behavior with a CFD fire model by simulating fire under a homogeneous tree crown and a heterogeneous tree crown modeled with FUEL3D, using two different levels of surface fire intensity. Model output is used to estimate the probability of tree mortality, linking fire behavior and fire effects at the scale of an individual tree. We discovered that variability within a tree crown altered the timing, magnitude and dynamics of how fire burned through the crown; effects varied with surface fire intensity. In the lower surface fire intensity case, the heterogeneous tree crown barely ignited and would likely survive, while the homogeneous tree had nearly 80% fuel consumption and an order of magnitude difference in total net radiative heat transfer. In the higher surface fire intensity case, both cases burned readily. Differences for the homogeneous tree between the two surface fire intensity cases were minimal but were dramatic for the heterogeneous tree. These results suggest that heterogeneity within the crown causes more conditional, threshold-like interactions with fire. We conclude with discussion of implications for fire behavior modeling and fire ecology.

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1. Introduction

Crown fires, fires which burn through vegetation canopies, pose significant challenges to fire managers (Albini and Stocks, 1986) often spreading rapidly via lofted firebrands (Wade and Ward, 1973) and burning with greater intensity and faster spread than surface fires (Rothermel, 1983). Prediction of the conditions under which crown fires initiate and propagate are thus of primary concern in fire management.

A number of models and decision support tools which predict fire spread in vegetation canopies have been developed. The systems used in Canada (Hirsch, 1996; Alexander et al., 2006) and Australia (Nobel et al., 1980) are empirical in nature, developed from correlative relationships observed in field studies, and predict fire spread as a function of weather and fuel conditions and the slope of the terrain; variability in fuels is not addressed as crown fuels are considered as a homogeneous single layer. This simplifying assumption is common to other systems used in Canada as well (Cruz et al., 2006). The systems used operationally in the United States (Finney, 1998; Scott, 1999; Reinhardt and Crookston, 2003; Andrews et al., 2005) are based primarily on a semi-empirical surface fire spread model (Rothermel, 1972) and have been extended to crown fire spread through links to Rothermel's empirical crown fire rate of spread model (Rothermel, 1991) via Van Wagner's crown fire initiation and propagation models (Van Wagner, 1977; Van Wagner, 1993). In this modeling system, surface fuels are assumed to be homogeneous, continuous and contiguous to the ground and crown fuels are considered as a homogeneous layer of uniform height above the ground, depth and bulk density; different mechanisms of heat transfer (i.e., radiative, convective or conductive) are not explicitly modeled, nor are transitory fire behaviors. Fuel models used as inputs to this modeling system consist of sets of

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parameters (e.g. surface area to volume, heat content and fuel load) describing homogeneous fuel beds (Anderson, 1982; Scott and Burgan, 2005).

The assumption of a homogeneous crown layer is thus a central component in current models used to predict crown fire behavior. In reality, vegetation is never homogenous nor continuous but this assumption may be reasonable at coarse scales for dense forests of trees very similar size and age, typified by the stands used in Van Wagner's analysis (Van Wagner, 1964). It is increasingly tenuous, however, when applied to stands characterized by variability in size and numbers of trees, where between-tree heterogeneity could be expected to be significant. Implicit in this assumption is that fuel variability at finer scales, such as within a tree crown, is unimportant to fire behavior. However, evidence suggests that fire behavior is sensitive to fine scale spatial variability, including size, shape and orientation of particles, and distance between them (Fons, 1946; Vogel and Williams, 1970; Weber, 1990; Bradstock and Gill, 1993; Burrows, 2001; Pimont et al., 2009). Recent critiques argue that the assumptions and empirical basis of the modeling framework used for crown fire in the United States are inconsistent with active spreading crown fire conditions and characteristics (Cohen et al., 2006) and often result in inaccurate predictions (Cruz and Alexander, 2010).

Fundamentally, crown fire occurs at the intersection of fire and vegetation canopies, both of which are sufficiently complex that modeling is needed to understand and explain the key processes involved. Advances in computing capabilities and simulation modeling techniques over the last two decades have opened up new possibilities for modeling fire behavior and fuels with greater detail.

Mechanistic physics-based fire behavior models have been recently developed which can address fuel heterogeneity (Mell et al., 1996, 2007, 2009; Linn, 1997; Morvan and Dupuy, 2001; Linn et al., 2002; Dupuy and Morvan, 2005; Linn et al., 2005). These computational fluid dynamics (CFD) models simulate fire behavior dynamically over time within a three-dimensional spatial domain, describing the dynamics according to equations for the conservation of mass, momentum, energy and species. Unlike operational models, which assume steady state rates of fire spread (Rothermel, 1972), CFD models are self-determining and are thus capable of addressing fire-fuel interactions arising from spatial variability within the fuel bed, and fire-atmosphere interactions. CFD models have been used to model fire at the scale of individual trees (Mell et al., 2009), but to date have not been used to explore the potential impacts of heterogeneity within the crown of an individual tree. One potential limitation is that these complex fire models require detailed 3D fuels inputs which are difficult to directly measure. Standard forestry inventory data only provide lists of trees and basic attributes, such as height and diameter, and lack the more fundamental fuel characteristics such as bulk density. While methods have been developed to estimate bulk density at the stand scale through indirect measurements (Keane et al., 2005), more sophisticated approaches, typically involving modeling, are required to address this need at finer spatial scales.

Developments in models of plant structure and function, referred to as functional structural plant models (FSPMs) (Godin and Sinoquet, 2005), also offer new opportunities for improving our understanding of crown fire behavior, particularly with respect to the nature of vegetative canopies. FSPMs generally model plants as spatially explicit 3D structures, often with extremely realistic detail (Godin et al., 2004; Kang et al., 2008; Pradal et al., 2009). Plant architecture can be represented in a number of ways (Godin, 2000) which facilitate analyses of numerous aspects of plant growth, physiology and interaction with the environment (Balandier et al., 2000; Mathieu et al., 2009).

Unlike the fuel models used to provide inputs to operational fire behavior models, which assume homogeneous fuel characteristics, FSPMs are capable of modeling vegetation with substantial detail, characterizing not only the structure and composition of plants (Prusinkiewicz, 2004) but also dynamic processes such as carbon allocation, growth, hydraulic function (Balandier et al., 2000; Allen et al., 2005) and biomechanical properties (Jirasek et al., 2000). Of particular relevance to the problem of crown fire are models that address interactions between plants and the environment (Sinoquet and Le Roux, 2000; Sinoquet et al., 2001). For example, Pimont et al. (2009) recently employed an FSPM to explore the effect of heterogeneity in canopy fuel on radiative heat transfer. Although the use of FSPMs to describe fuels is a relatively new concept (Caraglio et al., 2007), the potential value that advanced plant models can contribute to consideration of fuel and fire interactions is considerable.

In this investigation we use modeling to explore the effect of heterogeneity in bulk density within a tree crown on fire behavior. Using a simple FSPM, FUEL3D, we simulate the spatial distribution of biomass in an individual ponderosa pine. Then, using a CFD fire behavior model, WFDS (Mell et al., 2009), we conduct a numerical experiment in which we compare fire behavior between the spatially variable tree modeled with FUEL3D and a homogeneous crown that has the same gross dimensions and amount of fuel. We then explicitly link fire behavior and fire effects at the scale of an individual tree by using a statistical model to predict the probability of fire induced mortality for these trees. We conclude with discussion of the ecological and management implications of our simulation study.

2. Model description

2.1. Overview

FUEL3D is a static, stochastic, functional structural plant model (FSPM) designed to characterize the spatial distribution of biomass within a tree crown for the purpose of facilitating detailed simulations of fire behavior. FUEL3D provides a means by which typical stand inventory data, such as tree heights, diameters and other basic measurements, can be used to develop detailed inputs to advanced fire behavior models. Fig. 1 presents a conceptual diagram of the FUEL3D model, and a list of symbols for the FUEL3D model is presented in Table 1. Biomass quantities, determined with empirical equations, are distributed in space as a collection of simple solid shapes (e.g. cylinders and frustums) using a pipe model based approach (Shinozaki et al., 1964) and a recursive branching algorithm. These structures are stored in a spatially explicit database which tracks their coordinates, surface area, volume and mass, as well as additional attributes relating to combustion characteristics, such as silica content, material density and heat of combustion, determined from the literature. Attributes which may be more dynamic in nature, such as fuel moisture content, are assigned. Other descriptors link each object in the database to others with which it shares a common identity (e.g., all pieces of the same branch, all parts of the same tree). These descriptors provide the capability of extracting subsets of a tree on the basis of a simple query (e.g. a particular branch identity number) and also facilitate analysis and post-processing of model outputs for visualization and summarization.

To provide inputs for CFD fire behavior models, or other 3D models, the spatially explicit database is summarized to volumetric cells (voxels). In this way the model represents vegetation both as explicit objects in space and as summarized quantities within specified volumes. An important aspect of this approach is that the same set of detailed 3D objects, with explicit coordinates and dimensions, can be summarized to voxels at different resolutions, effectively spanning a range of spatial scales. Although FUEL3D can be used to model a broader range of plants, such as shrubs, grasses