

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

Russell A. Parsons<sup>a,\*</sup>, William E. Mell<sup>b</sup>, Peter McCauley<sup>c</sup>

<sup>a</sup> USDA Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, 5775 Hwy 10 West, Missoula, MT 59808, USA

<sup>b</sup> Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD, USA

<sup>c</sup> Washington State University, Spokane, WA, USA

### ARTICLE INFO

#### Article history:

Received 25 February 2010

Received in revised form 23 October 2010

Accepted 28 October 2010

Available online 21 November 2010

#### Keywords:

Functional structural plant model (FSPM)

Crown fuel

Pipe model theory

CFD

Fire behavior

### ABSTRACT

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.

Published by Elsevier B.V.

### 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 pre-

dict 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

\* Corresponding author. Tel.: +1 406 329 4872; fax: +1 406 329 4877.

E-mail addresses: [rparsons@fs.fed.us](mailto:rparsons@fs.fed.us), [rpfuel@gmail.com](mailto:rpfuel@gmail.com) (R.A. Parsons).

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.

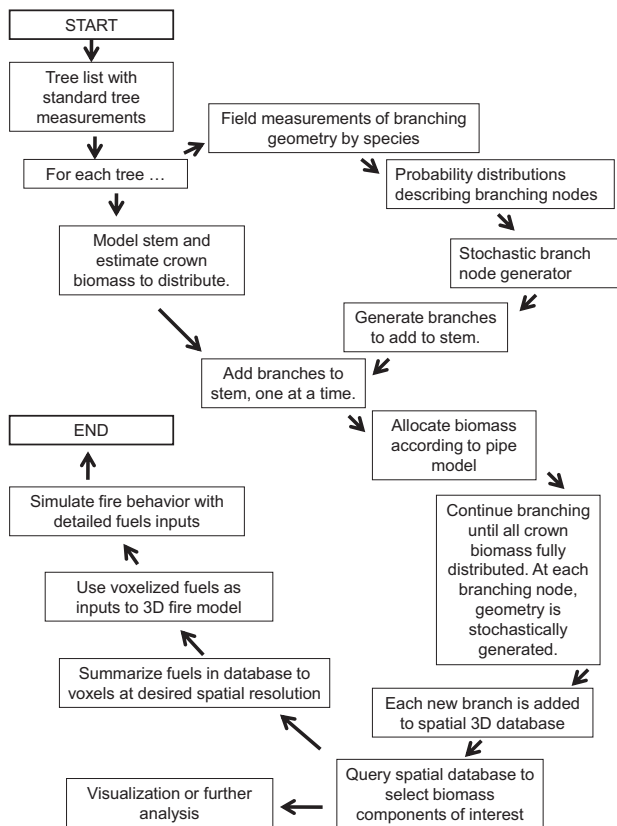
In this investigation we use modeling to explore the effect of heterogeneity in bulk density within a tree crown on fire behavior. Using a simple FSPM, FUEL3D, we simulate the spatial distribution of biomass in an individual ponderosa pine. Then, using a CFD fire behavior model, WFDS (Mell et al., 2009), 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



**Fig. 1.** Schematic diagram presenting an overview of the FUEL3D model. FUEL3D is a functional structural plant model designed to investigate the effects of crown fuel heterogeneity on fire behavior. Each tree is different, with branching architecture modeled stochastically by sampling from probability distribution functions and histograms parameterized from field measurements. The output of the model is a database of spatially explicit biomass components, such as branch segments or foliage needles; these objects are then summarized to 3D voxels for input to a physics based fire behavior model, WFDS.

and deciduous trees, these developments are still in preliminary stages. In this study we utilize FUEL3D to model a Ponderosa pine tree.

FUEL3D relies theoretically on the pipe model theory (PMT) (Shinozaki et al., 1964), which envisions trees as a collection of “unit pipes”, where a unit pipe transports water to a unit of foliage. This balance between water supply and demand provides for a straightforward and generally accurate estimation of biomass quantities and allometric scaling relationships. For this reason, despite criticism of its simplistic portrayal of plant function such as hydrodynamics (Tyree and Ewers, 1991) the pipe model plays a key role in many contemporary forest models (Robichaud and Methven, 1992; Chiba, 1998; Perttunen et al., 1998; MacFarlane et al., 2000; Alexandrov, 2008) and is widely cited in the literature (Grace, 1997).

Spatially explicit models of trees and shrubs have been developed with different levels of detail. The most common applications of such models are light dynamics and plant growth models (see Brunner, 1998; Busing and Mailly, 2004 for reviews of several such models, respectively). A common approach is to represent trees and shrubs crowns as simple geometric forms, such as cylinders, cones or ellipsoids (e.g. Canham et al., 1999; Kuuluvainen and Pukkala, 1989; Pukkala et al., 1993). Such representations are limited to particular scales because detail within the tree crown is not modeled. Tree crowns are fractal-like objects, having properties and geometry that combine aspects of both two dimensional and three dimensional bodies and which exhibit self-similarity across a range

**Table 1**  
List of symbols and their meanings for the FUEL3D model.

Symbol	
<b>Individual tree measurements from inventory</b>	
HT	Tree height (m)
R	Crown ratio, proportion of total tree height occupied by continuous live crown
DBH	Diameter at breast height (cm)
SPP	Species code; used to link species specific geometry parameters
<b>Symbols used in FUEL3D model</b>	
$A_{breast\ height}$	Cross-sectional area at breast height
$A_{crown\ base}$	Cross-sectional area at base of live crown
$A_{bn}$	Cross-sectional area available for branching at the $n$ th whorl
$A_{Bp}$	Cross-sectional area of a parent segment
$A_{Bi}$	Cross-sectional area of a particular child segment at a branching node
$A_{Si}$	Cross-sectional area for stem at whorl $i$
$A_{Bi}$	Cross-sectional area for branch wood at whorl $i$
$C_1$	Starter segment length/estimated branch total length
$C_2$	Proportion of biomass allocated to dominant child at a branching node
$r_z$	Stem radius at height $z$
$L_T$	Predicted total branch length
$\ell_0$	Initial segment length
$l$	A segment length
$\gamma$	Ratio of child segment length to parent segment length
$m$	Number of child branches at a branching node
$M_T$	Total woody biomass (kg)
$M_B$	Branch woody biomass in crown (kg)
$M_S$	Stem woody biomass (kg)
$M_F$	Foliar biomass
$M_{Bi}$	Branch biomass assigned to a particular whorl
$M_{Fi}$	Foliar biomass assigned to a particular whorl
$M_{Bij}$	Branch woody biomass assigned to branch $j$ on whorl $i$
$M_{Fij}$	Foliar biomass assigned to branch $j$ on whorl $i$
$n$	Number of whorls on the main stem
$\rho$	Wood density, assumed constant throughout tree
$\rho_f$	Average foliar material density
$V_T$	Total woody volume ( $M^3$ )
$V_B$	Volume of branch wood ( $m^3$ )
$V_S$	Stem wood volume ( $m^3$ )
$r_0$	Stem radius at tree base
$r_1$	Stem radius at breast height
$r_2$	Stem radius at crown base
$r_3$	Minimum radius, measured at ends of branches
$x$	$x$ coordinate
$y$	$y$ coordinate
$z$	$z$ coordinate

of scales (Mandelbrot, 1983; Godin, 2000; Godin et al., 2004). A number of FSPMs have been developed which employ fractal methods to simulate plant architecture for tree crowns (Berezovskaya et al., 1997; Chen et al., 1994) or for root systems (Ozier-Lafontaine et al., 1999; Richardson and zu Dohna, 2003). Such approaches are useful in representing canopy fuels because they more accurately capture the natural pattern of clumps of fuel separated by gaps, such as those between needles and between branches. FUEL3D shares some similarities with these approaches, largely through its use of recursive branching, described later in this paper, to construct a tree crown as a series of modular components. However, while it produces simulated plant architectures that are fractal-like, FUEL3D robust theoretical analysis of fractal behaviors (e.g. West et al., 1997) is not a primary objective of the model.

## 2.2. Model formulation

### 2.2.1. Biomass estimation

FUEL3D begins with estimation of biomass quantities. Once these quantities are determined, the model then distributes them in space until they are used up. The FUEL3D model iterates through a tree list, simulating one tree at a time. For each tree, foliage biomass,  $M_F$ , and crown branchwood,  $M_B$ , are estimated with biomass equa-

tions. Multiple biomass equations are included for various species in a database and selection of which biomass equation to use is a user input. The default biomass equation is of a form that incorporates the crown ratio,  $R$  (proportion of total tree height occupied by continuous live crown) as inclusion of this variable has been demonstrated to significantly improve the accuracy of biomass estimates (Brown, 1978; Valentine et al., 1994a,b; Hoffmann and Usoltsev, 2002). The advantage of using an empirical biomass equation is that biomass estimates will be more accurate for specific locations. In the event that a more specific biomass equation is not to be found, the model defaults to a more general equation (Jenkins et al., 2003).

For Ponderosa pine (*Pinus ponderosa*), crown biomass is estimated using the equation provided by Brown (1978). Brown's equation calculates a total crown biomass (foliage + crown branchwood) as

$$M_C = e^{(2.2812 \ln(d) + 1.5098(\ln(R)) - 3.0957)}; \quad (1)$$

Foliage biomass,  $M_F$ , is then calculated as a proportion of that total as

$$p_{fol} = 0.558e^{(-0.0457d)}, \quad (2)$$

where  $M_C$  is the total biomass within the crown,  $R$  is the crown ratio, calculated (for the purposes of the Brown's equation) as  $10(\text{crown length}/\text{tree height})$ ,  $d$  is tree diameter at breast height in inches, and output biomass is measured in pounds. The crown branchwood biomass,  $M_B$  is calculated by subtraction, as  $M_C - M_F$ .

### 2.2.2. Distributing biomass in space

With the crown branchwood biomass,  $M_B$ , and foliar biomass,  $M_F$ , determined, FUEL3D proceeds to distribute those quantities in space. For monopodial species (having a single dominant stem) such as most conifer trees, FUEL3D begins with the tree bole. The tree bole is modeled as a quadratic polynomial tapering column (Goulding and Murray, 1975) of the form

$$r_z = p_1 z^2 + p_2 z + p_3 \quad (3)$$

where  $r_z$  is the radius of the tree bole at height  $z$  and  $p_1$ ,  $p_2$ , and  $p_3$  are coefficients of the second order polynomial. The polynomial coefficients are determined through a nonlinear fitting procedure for each tree using four points: the radius at the base of the bole,  $r_0$ , predicted from species specific bole taper equations (for Ponderosa pine, Alemdag and Honer, 1977) and  $r_1$ , the radius at breast height (measured), radius at the base of the live crown,  $r_2$ , described below, and a minimum radius,  $r_3$ , estimated from field measurements at the ends of branches, and assumed to be the radius at the top of the tree (Fig. 2). In fitting the polynomial to predict bole radius as a function of height, the coordinate at the top of the tree is weighted to constrain the polynomial to positive bole radius values.

The radius at the base of the live crown,  $r_2$ , is estimated as

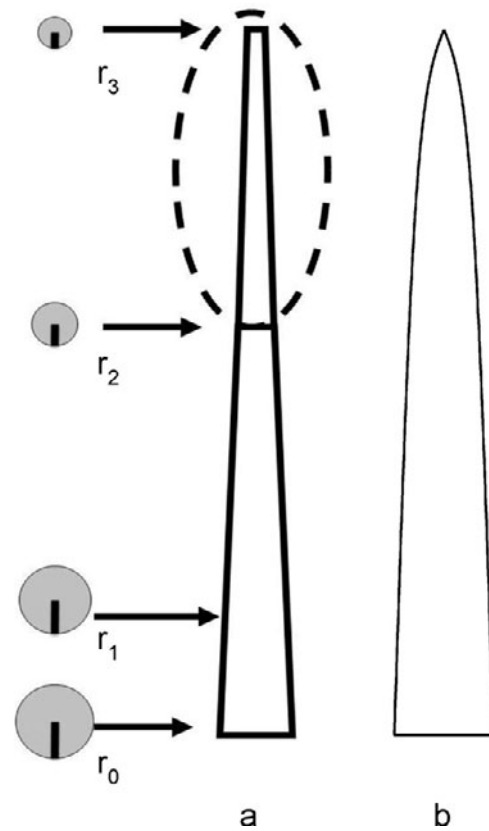
$$r_2 = \sqrt{\frac{A_{\text{crown base}}}{\pi}} \quad (4)$$

and

$$A_{\text{crown base}} = R A_{\text{breast height}} \quad (5)$$

where  $A_{\text{breast height}}$  is the cross-sectional area at breast height, and  $R$  is the crown ratio (proportion of total height occupied by contiguous crown) (Valentine et al., 1994a). Following the pipe model theory, biomass is proportional to the cross-sectional area at the base of the live crown,  $A_{\text{crown base}}$ . Non-conducting heartwood is assumed to be present in the bole below the crown base, resulting in a tapered form and is accounted for in the quadratic tapering.

Woody biomass within the stem,  $M_S$ , is determined by integrating the polynomial, Eq. (3), and multiplying that volume by the



**Fig. 2.** Schematic diagram of (a) radii from four points on the tree stem used in the FUEL3D model to model the tree bole with (a and b) quadratic polynomial. The polynomial is fitted to each individual tree. Of the four points, only  $r_1$ , radius at breast height, is required as an input for each tree;  $r_0$ , radius at the base of the stem, is predicted from species specific bole taper equations,  $r_2$ , radius at base of live crown, is estimated from  $r_1$  and the crown ratio, and  $r_3$ , average radius at tip of a branch, is estimated from field measurements taken to describe a species.

density,  $\rho$ ; for this study a standard wood density for ponderosa pine, of  $400 \text{ kg m}^{-3}$ , was used (Alden et al., 2000). Woody branch biomass,  $M_B$  is provided by the biomass equation. The total woody biomass,  $M_T$ , is the sum of these two quantities. The corresponding woody biomass volume,  $V_T$ , is the sum of the volume of the bole and the volume of the branch wood,  $V_B$ , calculated as  $\rho M_B$ . Consistent with the pipe model, this volume is considered as a cylinder for which the base is  $A_{\text{crown base}}$ . The separation of the volume contributed by the stem and the volume contributed by branch wood gives FUEL3D ample flexibility for representing the distribution of biomass; inventory data provide tree height, height to crown base, and diameter at breast height, while biomass equations set the quantity of crown foliage and branch wood to distribute in space.

Starting at the base of the live crown and continuing upward, the stem is divided into a series of polynomial sections,  $1, \dots, n$ , which represent whorls of branches on the stem and the spaces between them. Inter-whorl section lengths are stochastically generated from probability distribution functions parameterized from field data, and described in the next section.

At each whorl, a portion of the cross-sectional area is diverted laterally to branches, while the remainder continues farther up in the main stem of the tree. The proportion of  $A_{\text{crown base}}$  cross-sectional area used by the tree stem at any whorl  $i$ ,  $A_{Si}$ , at a given height  $z$ , is calculated from the polynomial as

$$A_{Si} = A_z = \pi r_z^2 \quad (6)$$

where the radius,  $r_z$ , at any height  $z$  is provided in Eq. (3). The cross-sectional area that is available to be diverted laterally to branches



at that whorl,  $A_{Bi}$ , is then

$$A_{Bi} = A_{crown\ base} - A_{Si} - \sum_1^{i-1} A_B \quad (7)$$

Foliar biomass,  $M_{Fi}$ , and crown branchwood,  $M_{Bi}$ , are allocated to the branches which comprise whorl  $i$ , based on the cross-sectional area.

$$M_{Fi} = M_F \frac{A_{Bi}}{A_{crown\ base}} \quad (8)$$

and

$$M_{Bi} = M_B \frac{A_{Bi}}{A_{crown\ base}} \quad (9)$$

In other words, as cross-sectional area (and corresponding biomass quantities) is diverted laterally to branches, the cross-sectional area available for branches above that point is reduced accordingly. In this manner, cross-sectional area at the base of the live crown, and corresponding biomass quantities, are conserved, in strict accordance with the pipe model.

### 2.2.3. Stochasticity in branching architecture

Variability in branching architecture is readily observed in real plants and thus has been applied in numerous FSPMs (Ford, 1987; Kurth, 1994; Kang et al., 2008). Durand et al. (2005) developed a statistical approach for identifying areas within a 3D digitized plant where morphological characteristics are similar, and where they change.

FUEL3D employs a more simplistic stochastic process to address variability in branching architecture, where field data are used to characterize branching architecture by branch order and variability is described with probability distribution functions. These probability distribution functions are then accessed during the simulation of a tree. Each whorl on the main stem, as well as on subsequent smaller branches, is modeled as a branching node, consisting of a parent segment which splits into two or more child segments. Characteristics of each node are modeled stochastically, drawn from the distributions parameterized from field data; in this manner, variability observed in the field is retained in the model. Different types of characteristics are modeled with different forms. Discrete quantities, such as the number of branches,  $m$ , at a given whorl,  $i$ , are drawn from histograms, while continuous variables, such as orientation angles, are drawn from Beta probability distribution functions, described below. The Beta distribution was selected because it is flexible and bounded at both ends, which constrains output values to realistic ranges and avoids issues associated with heavy tailed distributions (Evans et al., 1993).

For each characteristic, distributions are fit by branch order; if differences between branch orders are not substantial, data are pooled and distribution parameters are applied to all applicable branch orders. This approach ensures that changes in architecture which may manifest themselves at different branch orders are maintained. Each whorl thus may have different numbers of branches and geometry.

The general form of the probability density function of the Beta distribution, bounded in the range  $a \leq x \leq b$ , where  $a$  and  $b$  are lower and upper bounds, respectively, and  $v$  and  $w$  are shape parameters, required to have positive values ( $v > 0, w > 0$ ), is

$$f(x|a, b, v, w) = \frac{(x-a)^{v-1}(b-x)^{w-1}}{\beta(v, w)(b-a)^{v+w-1}} \quad (10)$$

$\beta(v, w)$  is the Beta function, defined as

$$\beta(v, w) = \int_0^1 u^{v-1}(1-u)^{w-1} du \quad (11)$$

depending on the values of the shape parameters  $v$  and  $w$ , the beta distribution can exhibit a wide variety of forms. Incorporating these probability distributions within the FUEL3D model ensures that variability observed within field data is preserved in model output.

Within any given whorl, each branch is assigned an initial segment length,  $\ell_0$ , set as a proportion of the expected total branch length,  $L_T$ , as follows:

$$\ell_0 = L_T C_1 \quad (12)$$

where  $L_T$  is total branch length predicted empirically from branch diameter, and  $C_1$  is drawn from a Beta distribution parameterized from field data, and defined by the ratio of the length from the branch base to the first live second order branch to the total branch length.

FUEL3D produces a list of branching nodes, for all whorls on the main stem. Each branch is specified by an initial segment, orientation, branch basal diameter, and associated total biomass quantities. This process of building the branching nodes along the stem simply enables modeling of branches one at a time, which greatly reduces the computational resources required by the model. As each branching node is produced it is added to the spatially explicit database describing the tree.

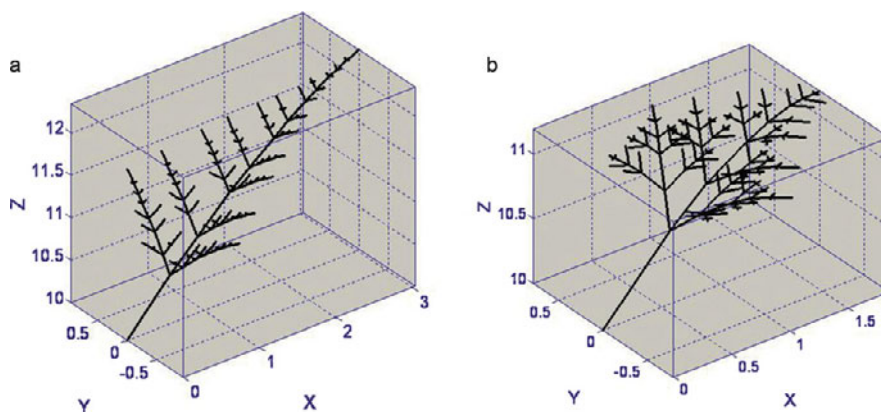
Each branch is modeled with a recursive (self-referencing) algorithm, similar to other fractal tree models (Niklas, 1986; Berezovskaya et al., 1997; van Noordwijk and Mulia, 2002). The algorithm extends itself, splits into smaller branches, which themselves split into smaller branches, and so on until the biomass quantities allocated to the branch are exhausted. As in the branching nodes on the stem, cross-sectional area is preserved, and is used to allocate biomass; each branching node is stochastically generated, producing branching structures that mimic the variability observed in real trees.

Using field data for parameterization, FUEL3D sets the proportion of cross-sectional area, and corresponding biomass, in the dominant child segment. This enables FUEL3D to account in a simple manner for apical control, in which the main, usually central portion, of the branch is larger and longer than the smaller branches which extend off of it (Fig. 3), similar to the approach used in other static fractal models in which child segments can be of unequal size (Ozier-Lafontaine et al., 1999; Richardson and zu Dohna, 2003).

A particular branching node is created with orientations between component segments but generic dimensions. Its position is also generic, with the base at the origin ( $x=0, y=0$ , and  $z=0$ ), with the main segment (which would typically serve as the continuing extension of the parent branch segment) oriented along the  $z$ -axis. After a particular branching node is generated, its dimensions are scaled such that biomass is accounted for, and it is rotated and translated in space, following standard rotation matrices, such that its orientation is consistent with the parent segment and that it extends from the distal end of the parent segment. Similar to the approach used by Richardson and zu Dohna (2003), segment lengths are scaled as

$$\gamma = p^{1/3} \quad (13)$$

where  $p$  is the proportion of the sum cross-sectional area for a particular child segment and  $\gamma$  is the ratio of the child length to the parent segment length. Each segment continues to branch, producing a new branching node consisting of some number of child segments, until it reaches a minimum diameter, measured from field data. When this occurs the algorithm stops branching and constructs a terminal structure. For conifers, terminal structures consist of a short branch segment in which foliar biomass is divided into individual needles, arranged in fascicles (clumps); fascicles are distributed on the branch segment with gaps between them based on field measurements. Measurements of needle dimensions and



**Fig. 3.** Example of two branches modeled with FUEL3D, shown as line figures. A change in the allocation of biomass to the dominant branch segment has resulted in a longer branch and a different geometry. Branches shown in this figure were developed without variability in angles or lengths, such that effect of biomass allocation to the central segment in a branching node would be clearer.

angles are part of the detailed data collection used to parameterize a species. FUEL3D can model the position of each individual needle. However, for many purposes, such as summarization to voxels (described below), this has a high cost in computation time. For this reason, terminal structures are generally represented with simple cylindrical bounding volumes which account for biomass quantities within them. Bounding containers are also useful in characterizing whole crown volumes, facilitating analyses of fuel properties at coarser (less resolved) spatial scales.

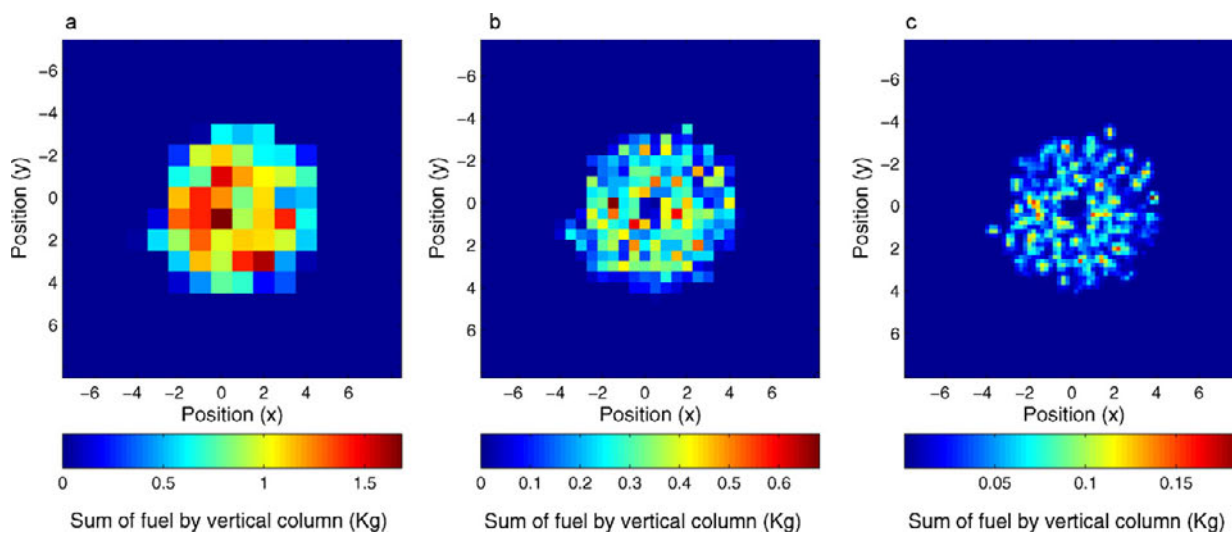
### 2.3. Summarization to discrete volumes

In order for the collection of branch segments and foliage which compose the simulated tree to be used in a numerical fire model it is necessary to convert the output data to values associated with three-dimensional grid cells, or voxels. This is done via a Monte Carlo integration approach, in which the volume of each segment or other component of the modeled biomass is populated with random points; these random points are then juxtaposed on the boundary lines of the mesh which define the three dimensional array. Biomass is apportioned among the grid cells which contain points on the basis of the proportion of points found in each grid cell. A similar procedure is followed for surface area, where ran-

dom points are constrained to be located on the surface of the modeled biomass component. In this manner the total quantities are preserved across whatever spatial scale is desired. Fig. 4 illustrates the spatial pattern of fuels within a small tree modeled with FUEL3D, and then summarized to voxels at three different cell resolutions (0.5 m, 0.25 m and 0.1 m). This summarization approach enables the FUEL3D model to characterize wildland fuels across a spectrum of spatial scales. Summarization to voxels can be carried out for different fuel components, such as within a particular range of diameters, by querying the spatial database prior to summarization.

### 2.4. Field data collection

Field measurements used to parameterize FUEL3D for ponderosa pine in this study came primarily from two sources. Relationships predicting branch biomass quantities and gross dimensions (total length and width) from branch basal diameter were provided by an intensive, destructive sampling field study, known as the Crown Fuels Study (CROWNFUELS) (Keane et al., 2005; Reinhardt et al., 2007); these data were used extensively in preliminary development of the FUEL3D model (Parsons, 2006). For this study, additional destructive sampling, referred to as the



**Fig. 4.** Demonstration of the spatial pattern of fuels within a small tree modeled with FUEL3D and then summarized to voxels at three different spatial resolutions: (a) 0.5 m; (b) 0.25 m; (c) 0.1 m.

**Table 2**

Parameters used in FUEL3D model determined for Ponderosa pine from field data. Source 1 is data collected at Ninemile, Montana in 2007, Source 2 is data collected as part of CROWNFUELS study at Ninemile, MT 2000–2002.

Parameter	Source	Description						
<b>Empirical constants and relationships</b>								
$r_3$	1	Minimum branch radius (mm)	2.1					
$L_T$	2	Predicted total branch length $L_T = 0.6369d^{0.8909}$ , $R^2 = 0.968$						
Parameter	Source	Description	Lower bound	Upper bound	Shape parameters			
			<i>a</i>	<i>b</i>	<i>v</i>	<i>w</i>		
<b>Continuous variables modeled with Beta distribution</b>								
$L_i$	1	Inter-whorl length, along main stem, for a whorl, <i>i</i> (cm)	5	95	4.8	16.7		
$C_1$	1	Starter segment length proportion of total length	0.1	0.3	27.4	31.2		
$C_2$	1	Proportion of biomass allocated to dominant child at node	0.4	0.9	5.1	8.2		
$Angle_{.1}$	1	Angle between axes of parent segment and child segment	42	91	14.9	5.3		
$Angle_{.2}$	1	Angular variability, perpendicular to $Angle_{.1}$	1	17	13.8	17.4		
<b>Discrete variables, sampled from empirical histograms</b>								
$m_{first\ order}$	1	Number of observations, by bin (388 total)	198	126	54	5	4	1
		Number of branches at a whorl, incl. continuing parent	2	3	4	5	6	7
$m_{higher\ order}$	1	Number of observations, by bin (687 total)	281	209	121	50	21	5
		Number of branches at a whorl, incl. continuing parent	2	3	4	5	6	7

BRANCHGEOM study, was carried out at Ninemile on the Lolo National Forest near Missoula, Montana in July 2007. The purpose of the BRANCHGEOM study was to characterize branching nodes for ponderosa pine. Ten Ponderosa pine trees were selected from the same stand and were felled using a restraining system so the tree crowns would not be damaged by felling. Measurements were taken at three levels: for the whole tree, whorl (on main stem) and on and within individual branches. For each tree, total height, diameter at breast height, and height to the base of the live crown were measured. Whorl measurements included height above the ground, stem diameter above and below the whorl and number of first order branches. For each first order branch, basal diameters, angles relative to the main stem, and lengths to next branching node were measured. Branch diameters were taken with metric digital calipers and angles were measured with transparent plastic angle gauges. These measurements described branching nodes along the main stem. Similar measurements were made within branches to capture geometry at higher branching orders, based on a subsample of every third branch. Geometry of foliage clumps, which represent a special case of branching node, was characterized with additional sub sampling. Finally, digital images were taken of each sub-sampled branch, with and without foliage, with a metric ruler for scale, to capture whole branch geometry. Basic measurements of angles, lengths and diameters made post-field upon these images provided additional data describing branching geometry. Additional measurements, such as branch curvature, were made upon these images post field using image processing software but ultimately were not explicitly used in the model formulation. Altogether 388 first order branching nodes and 687 higher order branching nodes were described. Geometric variability within this population of branching nodes was characterized statistically by branching order. Parameter estimates for the Beta

distribution characterizing geometric branching variability were made with Maximum Likelihood Estimation (MLE) using the statistical software, R. Data were pooled if analysis revealed insignificant differences between branch orders.

### 2.5. Fire behavior simulation

We tested the effect of variability in the spatial distribution of biomass within the crown of an individual tree on fire behavior with the Wildland-Urban Interface Fire Dynamics Simulator (WFDS) model (Mell et al., 2009). WFDS is a recent extension of the Fire Dynamics Simulator (FDS version 5.2), a CFD fire model designed for structural fire applications. FDS was extended to accommodate vegetative fuels, such as foliage, as well as complex terrain and ambient wind flows. WFDS is a physical numerical fire behavior model in which CFD methods are used to solve the three-dimensional, time-dependent equations governing fluid motion, combustion, and heat transfer. A low-Mach number approximation (Rehm and Baum, 1978) of the governing equations for mass, momentum, and energy is used; a large-eddy simulation (LES) approach for turbulence modeling (Smagorinsky, 1963) provides a time-dependent, coarse-grained numerical solution to those equations. A direct solver for the pressure Poisson equation significantly speeds up calculations compared to iterative methods. WFDS has been used in domains of 1500 m × 1500 m for the simulation of Australian grassland fires (Mell et al., 2007).

Our simulation experiment compared two different tree crowns: a spatially variable crown (V), modeled with FUEL3D, and a homogeneous crown (H), with the same total fuel quantity and gross dimensions as the spatially variable tree crown. We simulated fires under these two tree cases with two levels of surface fire intensity: Low (L), and High (H), for a total of four simulations: (HL,

**Table 3**

Summary of fire behavior simulation outputs. In right most column,  $P_{mort}$  refers to the probability of mortality calculated for each tree.

Solid fuel (kg)					Total net radiative heat transfer (kW)			$P_{mort}$
Label	Fuel	Consumed	% loss	Duration	Peak	Mean	Stdv	
HL	44.9060	35.7987	79.72	56.49	2677.90	343.63	651.69	0.9160
VL	44.9060	0.4184	00.93	54.80	229.35	74.51	77.34	0.2668
HH	44.9060	44.7963	99.76	52.70	2520.60	361.77	669.36	0.9868
VH	44.9060	38.0156	84.66	63.49	3015.62	462.87	801.82	0.9439



VL, HH, VH). Our numerical experiment is described in more detail below.

### 2.6. Example spatially variable tree crown, modeled with FUEL3D

We used the FUEL3D model to simulate the distribution of biomass within the crown of an individual ponderosa pine tree, with standard forest inventory measurements of stem diameter at breast height of 25.4 cm, an overall height of 10.0 m, height to live crown base of 1.5 m and an average crown radius of 2.5 m. The resulting spatially explicit database of woody components and foliage was then queried to extract all material  $\leq 6$  mm in diameter. Material of this diameter is considered to be “thermally thin” and dominates fire behavior due to its high surface area to volume ratio, and rapid interaction with incident heat fluxes.

The set of thermally thin fuel elements within the database was then summarized to cells 0.25 m on a side for input into the WFDS fire behavior model.

### 2.7. Homogeneous tree crown

The homogeneous case tree was modeled as a right frustum (truncated cone), with the same gross dimensions as the spatially variable tree crown described above; diameter at the base of the frustum was 5 m and diameter at the top was 1 m. The frustum was located the same height above the ground (1.5 m) and extended to the same height (10 m) as the tree modeled above.

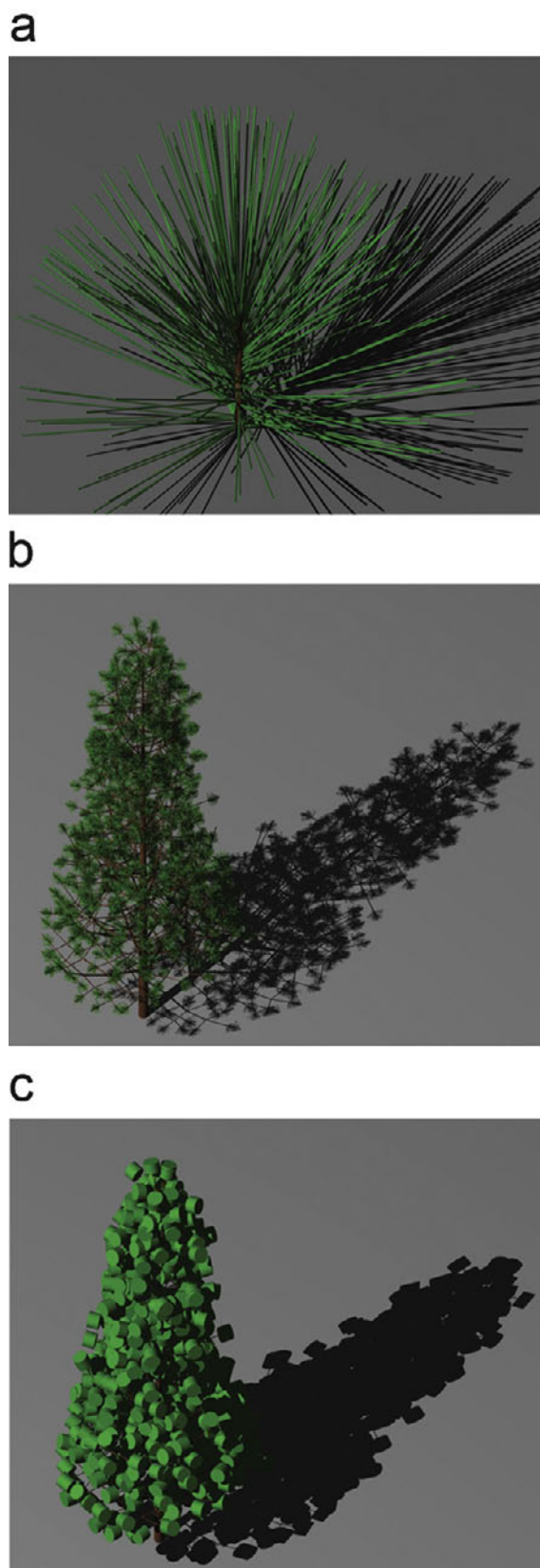
The spatial domain used in these simulations measured 24 m by 24 m by 20 m. Resolution was 0.25 m in all directions, for a numerical grid of 96 cells by 96 cells by 80 cells. This domain was partitioned into 9 equally sized sub-domains measuring  $32 \times 32$  by 80 cells and run on 9, 64 bit processors. Total simulation time was 180 s; with the nine processors, real time duration of each simulation averaged 2 h and 20 min.

The surface fire was simulated as user-prescribed advancing flaming front with a constant forward spread rate ( $0.1 \text{ m s}^{-1}$ ) and residence time (20 s). The intensity (heat release rate) was set at 300 kW for the low intensity cases (HL and VL) and 400 kW for the high intensity cases (HH and VH). This approach is not entirely realistic for real surface fuels because it eliminated some potential feedback interactions, such as impacts to the velocity field, between fire in the crown and the surface fire. The intent of this approach was to facilitate comparison between simulations by ensuring that the timing and geometry of the surface fire front was consistent across all simulations. For each simulation we tracked the solid fuel mass loss (dry mass and moisture mass) and total net radiative heat transfer ( $Q_{radnet}$ ) over time to facilitate comparison of fuel consumption and energy release. Simulation outputs were summarized in graphs and tables. Total net radiative heat transfer was calculated as

$$Q_{radnet} = \sum_j \int \nabla \cdot q_{rad} dV_j \quad (14)$$

where the sum is over all  $j$  cells comprising the tree crown, and  $V_j$  is the volume of cell  $j$ .

To simplify the experiment, all fuel cells had the same fundamental combustion properties, with heat of combustion, defined as the heat released per kg of gaseous fuel, set at  $17,700 \text{ kg}^{-1}$  (Susott, 1982), surface area to volume ratio constant at  $4000 \text{ m}^{-1}$  and the drag coefficient was set at 0.375. A maximum burning rate was set as 0.4 as was the maximum dehydration rate, based on experiments of burning Douglas fir trees (Mell et al., 2009). Char fraction was set to 0.25, and foliar material density,  $\rho_f$ , was  $514 \text{ kg m}^{-3}$  (Mell et al., 2009). Fuel moisture content was constant at 90% on a dry weight basis. The only form of variability considered in our



**Fig. 5.** Simulated tree views—example visualizations of a Ponderosa pine tree (*Pinus ponderosa*) simulated with the FUEL3D model; geometry is parameterized from field data. The top figure (a) shows an individual needle clump, middle figure (b) shows a tree modeled with explicit spatial detail to the level of individual needles. For most purposes, this representation is unwieldy; for this reason, groups of detailed smaller structures can be represented with larger simple bounding volumes, such as cylinders, as shown in bottom figure (c). Visualization is done using a ray tracing program.



numerical experiment was thus variability in bulk density. Following the process of summarization to grid cells, each grid cell had a different quantity of fuel; this however exceeded the current capabilities of the WFDS model in terms of the number of fuel descriptions that could be handled. Fuels were therefore converted to categorical values with 100 different classes using a histogram approach.

2.8. Linking fire behavior and fire effects

For each of the four simulations (HL, VL, HH, and VH), we used an empirical tree mortality equation to assess the probability that the tree would be killed by the fire ( $P_{mort}$ ), using the equation:

$$P_{mort} = \frac{1}{e^{(-1.941+(6.315(1-e^{-w}))-(0.000535s^2))}} \quad (15)$$

where  $P_{mort}$  is the probability of mortality,  $s$  is the percent crown volume scorched, and  $w$  is the bark thickness in inches (Reinhardt and Ryan, 1988). Bark thickness was set at 0.63 in. (16 mm) based on observed bark thickness relationships for Ponderosa pine (Reinhardt and Keane, 1998).

3. Results

3.1. Field data collection

Branching architecture data collected from the BRANCHGEOM field study were analyzed independently by branch order. With the exception of the inter-whorl length,  $L_i$ , which is used only on the main stem, analysis found differences in parameter estimates for Beta distributions characterizing variability in branching were not sufficiently different to warrant modeling separately by branch order so data were pooled. Histograms characterizing numbers of child branches at a branching node were different enough between first order and other branch orders for separate histograms to be described. A summary of the parameters characterizing variability in branching architecture for Ponderosa pine is presented in Table 2.

3.2. Fire behavior simulation

3.2.1. Heterogeneous tree simulated with FUEL3D

Using the standard tree measurements as inputs to Eqs. (1) and (2), total crown biomass amounted to 99.233 kg of fuel of which

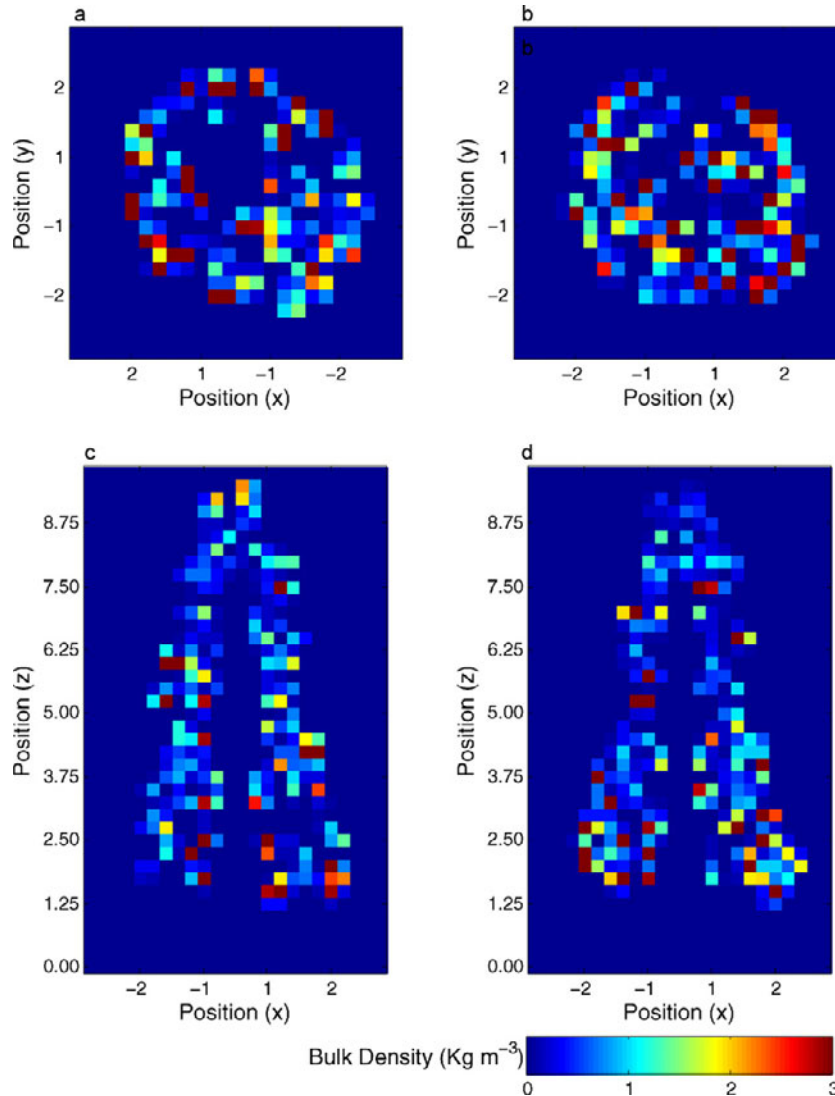
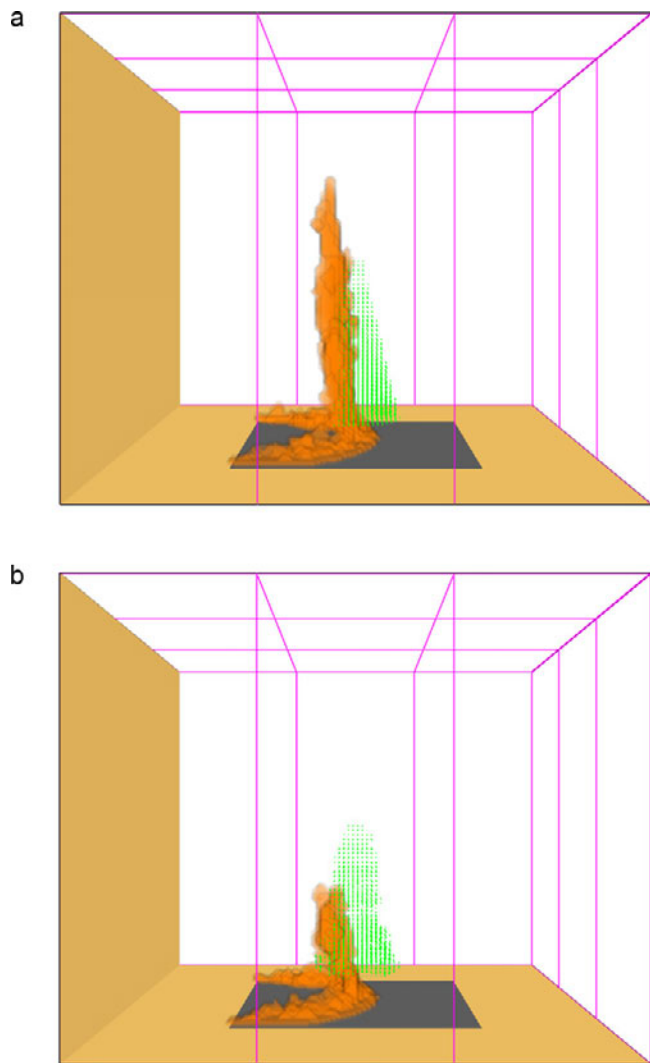


Fig. 6. Distribution of fuel bulk density within a tree crown simulated with FUEL3D, summarized to voxels 0.25 m on a side: (a) horizontal slice at  $z = 2.625$  m; (b) horizontal slice at  $z = 2.375$ ; (c) vertical slice at  $x = -0.125$ ; (d) vertical slice at  $x = 0.125$ .



**Fig. 7.** Visualization of two different numerical fire behavior simulations at the same point in time ( $t = 72$  s). Dots represent tree crowns while smooth areas to their left represent the fire. Two tree crowns are presented: a homogeneous tree (a) and a spatially variable tree simulated with the FUEL3D model (b). Both tree crowns had the same quantity of fuel and gross dimensions but bulk density varied within the crown in (b). Surface fires had identical timing, intensity and geometry in both cases.

foliar biomass comprised 34.435 kg. Simulation with FUEL3D produced a spatially explicit database of woody and foliage objects. Visualizations of these objects comprising the tree are presented in Fig. 5. A query of thermally thin woody material from this database yielded 10.471 kg, which with the foliage, produced a total of 44.9060 kg of thermally thin fuel within the simulated crown. Fig. 6 presents vertical and horizontal slices illustrating the range of bulk densities within this simulated crown after summarization to 0.25 m cells for use in the fire behavior simulation.

### 3.2.2. Homogeneous tree

The homogeneous tree was assigned the same total amount of thermally thin fuel, 44.9060 kg, and the same combustion properties as used in the spatially variable tree crown. The principal difference between the homogeneous crown and the spatially variable crown was that the entire volume of the homogeneous crown had the same bulk density ( $0.626 \text{ kg/m}^3$ ) while the spatially variable crown had a range of bulk densities.

### 3.2.3. Simulation results

Differences in the spatial configuration of fuels within the tree crown resulted in substantial differences in fire behavior (Table 3, Fig. 7); the nature and magnitude of these differences, however, varied with the intensity of the surface fire below the tree crowns (Fig. 8). In the lower surface fire intensity simulations, nearly 80% of the solid fuel was consumed in the homogeneous tree crown (HL), while only 0.4% of the solid fuel was consumed in the spatially variable crown, constituting a difference of nearly two orders in magnitude (Fig. 8). Similarly, total net radiative heat transfer,  $Q_{radnet}$ , reached a maximum of 2677.9 kW for the HL simulation but only rose to 229.4 kW for the spatially variable, low intensity simulation (VL) – a difference of more than an order of magnitude (Table 3, Fig. 8). Differences were less pronounced in the high intensity simulations (HH and VH); both tree crowns ignited, with nearly 100% fuel consumption in the homogeneous case and nearly 85% consumed in the spatially variable case. Spatial variability in fuels within the crown also resulted in changes in the timing, magnitude and dynamics of total net radiative heat transfer. The spatially variable tree crown started burning later, reached a higher peak flux (3015 kW versus 2520 kW), burned over a longer time period, and had more complex burn history, with two different peak fluxes separated by about 15 s. Predicted tree mortality was consistent with observed trends in fuel consumption, where the only tree predicted to survive was the VL case, with a 27% probability of mortality; all other cases had over 90% probability of mortality (Table 3).

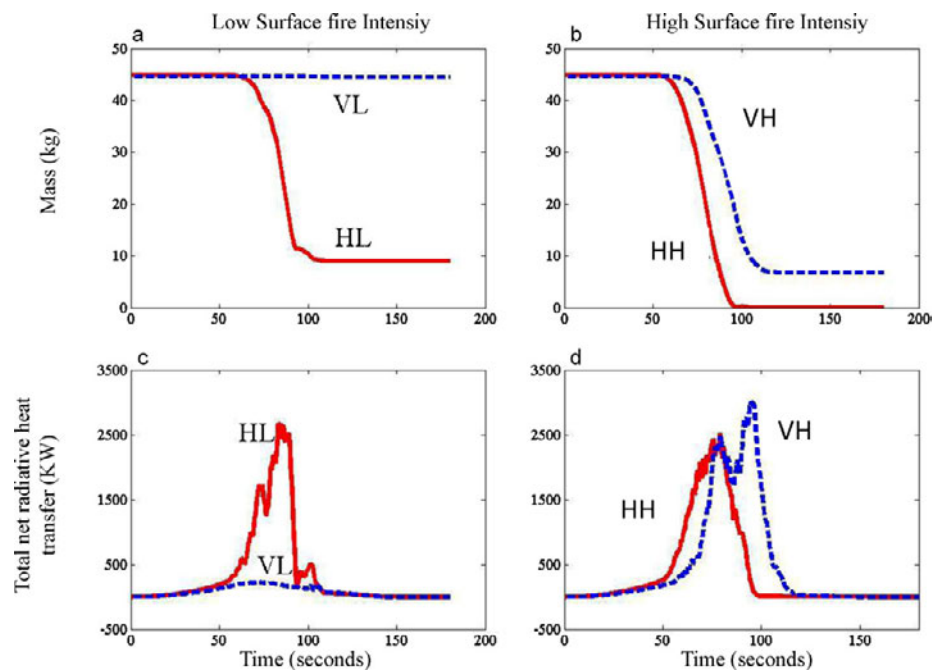
## 4. Discussion

### 4.1. Linking detailed fuel models with detailed fire models

In this study we used a relatively simple FSPM, FUEL3D, to develop inputs to an advanced fire behavior model, WFDS, and used simulation output from WFDS to predict an important fire effect, tree mortality. By linking a detailed, spatially explicit fuel model with a mechanistic fire behavior model we provide a framework that has significant potential to inform scientists and managers about a complex area, crown fire, which has so far only been modeled with fairly rudimentary approaches.

In comparison to many FSPMs, FUEL3D is quite simplistic, combining a simple pipe model biomass allocation with stochastic recursive branching to simulate structure. As a static model, FUEL3D does not simulate growth over time, nor does it deal with other aspects of plant physiology such as hydraulic relationships, carbon allocation or photosynthesis. This simplicity is by design. More complex, dynamic models of tree structure often require information that is difficult to obtain, such as a characterization of the growth environment over time (Balandier et al., 2000; Mathieu et al., 2009). Most questions relating to fire and fuels are more concerned with the immediate status of the fuel, and how it will burn at a given time, than with how the vegetation grew over time. By incorporating simple and typical measurements of tree height and height to the base of the live crown, and modeling branches one at a time within the crown, rather than building the whole tree mechanistically, FUEL3D retains the flexibility to represent individual measured trees. The simplicity of FUEL3D's design also makes it feasible to model fairly large numbers of trees, such as a tree list from inventory data. This improves its application with existing forestry inventory data and associated models.

More sophisticated FSPM's have been developed which deal with plant physiology, growth, and how plants respond to, and affect their environment, but have only rarely been applied to questions relating to disturbance such as fire. Our study, and other recent related developments (Pimont et al., 2009; Krivtsov et al., 2009) suggest that use of FSPMs in conjunction with advanced fire models are an emerging frontier. Rather than simply providing nec-



**Fig. 8.** Comparison of outputs from four different numerical fire behavior simulations with the WFDS model. Solid lines show outputs for the homogeneous tree crown while dash lines show outputs for the spatially variable tree crown produced with the FUEL3D model. The top two figures compare solid fuel consumption between the lower intensity surface fire case (a) and higher surface fire intensity case (b), while the lower two figures compare total net radiative heat transfer between the lower surface fire intensity case (c) and the higher surface fire intensity case (d). Total fuel quantities were identical for all four simulations.

essary inputs, detailed simulations of plant architecture can be used to actively inform, and possibly, refine, fire behavior models. For example, Pimont and others have demonstrated that the heterogeneity within wildland fuel structure significantly affects radiative heat transfer through the canopy (Pimont et al., 2009). Substantial gains in understanding could be made through a stronger incorporation of plant physiology into fuels research, particularly with respect to the underlying drivers of fire regimes in the context of dynamic climate and associated vegetation response. Such developments will be essential for consideration of potential outcomes of climate change.

#### 4.2. Comparison with traditional fire and fuel models

The modeling system presented here represents a substantial change from traditional approaches for modeling fuels and fire behavior. Traditional approaches assume unrealistic characteristics of vegetation (such as homogeneity and continuity (Anderson, 1982; Scott and Burgan, 2005)) in order to meet the assumptions of simple fire models (Rothermel, 1972). In contrast, our system models fuels explicitly in space and models fire mechanistically. The capability of the system to quantify variability in different wildland fuel characteristics across a spectrum of spatial scales greatly improves opportunities to evaluate different management alternatives, such as thinning and prescribed burning. Traditional approaches have been shown to be both inaccurate and also insensitive to changes in fuels (Alexander and Cruz, 2010). The differences in detail between fuels as represented for inputs to fire models (Anderson, 1982; Scott and Burgan, 2005) and fuels as inputs to fire effects models (Lutes et al., 2009) have required separate systems that are largely incompatible. In contrast, we link realistic fuels, fire behavior and fire effects calculations directly. While other researchers have used two-dimensional heat transfer modeling to predict cambial stem damage (Dickinson and Johnson, 2004), this is the first time that a three dimensional detailed CFD model has been used to evaluate mortality on an individual tree with this level of detail in simulation of fire through the tree crown.

Our work here constitutes an early, but important step in improving linkages between disturbance processes and ecosystem response, strengthening our understanding of fire ecology.

#### 4.3. Implications for fire ecology and fire behavior modeling

In our numerical experiment, we compared fire behavior between a homogeneous tree crown and a spatially variable tree crown produced with the FUEL3D model, for two different levels of surface fire intensity. We found that, despite the two trees having the same total quantity of fuel, variability within the tree crown resulted in very different fire behavior. At low surface fire intensity, the spatially variable tree crown did not burn while the homogeneous crown had nearly 80% fuel consumption. At higher surface fire intensity, the spatially variable tree crown was slower to ignite, but once burning, reached a higher peak total net radiative heat transfer, and exhibited more complex behavior. Thus, within a relatively narrow range of surface fire intensity, the homogeneous tree showed only incremental changes in fire behavior while the variable tree exhibited a much more dramatic response. This suggests a much more non-linear, threshold like response for the spatially variable tree than for the homogeneous tree. This has both implications for ecology and for fire behavior modeling.

Various authors have observed that, as a fire adapted species, Ponderosa pine has evolved to generate a surface fuel bed that is easily ignited and which favors frequent surface fire (Mutch, 1970; Habeck and Mutch, 1973). Similarly, many authors have discussed changes in fire behavior resulting from changes in stand density and structure in Ponderosa pine (Covington and Moore, 1994; Fulé et al., 1997, 2004; Moore et al., 2004), but relatively little work has been done at the scale of individual trees. It seems likely from our results that spatial variability within a tree crown could represent an adaptation tending to reduce the likelihood of sustained crown fire. More fundamental work along this line of inquiry is warranted.

Our numerical experiment has implications for fire behavior modeling, and particularly, for our ability to predict crown fire

behavior. The homogeneous tree crown burned faster and more consistently than the spatially variable crown. Fire behavior modeled with homogeneous fuels may thus tend to overestimate forward spread rates. Although we did not analyze this in this paper, we hypothesize that variability within the tree crown structure, and particularly the gaps within the crown, change the manner in which wind, as well as convective heat transfers, pass through the canopy. The slower burn time, and steeper threshold of response to an increase in surface fire intensity that we observed in the spatially variable tree crown suggests that variability tends to narrow the region of conditions in which propagation of fire can occur. If fire propagation through an individual crown is highly conditional, the predictability of fire spread may be limited. If this is the case, it may be necessary to adopt a probabilistic approach, in which key factors serve to shape probability distribution functions which describe whether individual trees catch fire, and by extension, whether crown fires propagate through whole stands of trees. More work is needed to examine the conditional nature of fire spread through tree crowns that is suggested by these results. Investigations linking more detailed models of fuels with advanced fire behavior models will help us to advance our understanding of what aspects of wildland fuels are most pertinent to fire behavior.

## Acknowledgements

We wish to acknowledge E. Reinhardt and R. Keane for use of data from their crown fuels field study. We greatly appreciate comments from two anonymous reviewers which were helpful in improving the clarity and organization of this manuscript. This study was supported by the USDA Rocky Mountain Research Station.

## References

- Albini, F.A., Stocks, B.J., 1986. Predicted and observed rates of spread of crown fires in immature jack pine. *Combustion Science and Technology* 48, 65–76.
- Alden, H.A., Highley, T.L., Norton, J., Kleinschmidt, S., DeGroot, R.C., Crawford, D., De Groot, R.C., Woodward, B., Hennon, P.E., Nakayama, F.S., 2000. *Softwoods of North America*. Techlines, 50.
- Alemdag, I.S., Honer, T.G., 1977. Metric Relationships Between Breast-height and Stump Diameters for Eleven Tree Species from Eastern and Central Canada. Information Report. Forest Management Institute Canada, Canada.
- Alexander, M.E., Cruz, M.G., Lopes, A.M.G., 2006. CFIS: a software tool for simulating crown fire initiation and spread. *Forest Ecology and Management* 234, S133–S1133.
- Alexandrov, G.A., 2008. Forest growth in the light of the thermodynamic theory of ecological systems. *Ecological Modelling* 216, 102–106.
- Allen, M.T., Prusinkiewicz, P., DeJong, T.M., 2005. Using L systems for modeling source–sink interactions, architecture and physiology of growing trees: the L PEACH model. *New Phytologist* 166, 869–880.
- Anderson, H.E., 1982. Aids to Determining Fuel Models for Estimating Fire Behavior. General Technical Report No. INT-122. USDA Forest Service Intermountain Research Station, Ogden, UT, USA.
- Andrews, P.L., Bevins, C.D., Seli, R.C., 2005. BehavePlus Fire Modeling System, Version 3: User's Guide No. RMRS-GTR-106WWW. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
- Balandier, P., Lacoite, A., LeRoux, X., Sinoquet, H., Cruiziat, P., LeDizes, S., 2000. SIMWAL: a structural–functional model simulating single walnut tree growth in response to climate and pruning. *Annals of Forest Science* 57, 571–585.
- Berezovskaya, F.S., Karev, G.P., Kisliuk, O.S., Khlebopros, R.G., Tsel'niker, Y.L., 1997. A fractal approach to computer-analytical modeling of tree crowns. *Trees-Structure and Function* 11, 323–327.
- Bradstock, R.A., Gill, A.M., 1993. Fire in semi-arid, mallee shrublands: size of flames from discrete fuel arrays and their role in the spread of fire. *International Journal of Wildland Fire* 3, 3–12.
- Brown, J.K., 1978. Weight and Density of Crowns of Rocky Mountain Conifers.
- Brunner, A., 1998. A light model for spatially explicit forest stand models. *Forest Ecology and Management*, 107.
- Burrows, N.D., 2001. Flame residence times and rates of weight loss of eucalypt forest fuel particles. *International Journal of Wildland Fire* 10, 137–143.
- Busing, R.T., Maily, D., 2004. Advances in spatial, individual-based modelling of forest dynamics. *Journal of Vegetation Science* 15, 831–842.
- Canham, C.D., Coates, K.D., Bartemucci, P., Quaglia, S., 1999. Measurement and modeling of spatially explicit variation in light transmission through interior cedar–hemlock forests of British Columbia. *Canadian Journal of Forest Research* 29, 1775–1783.
- Caraglio, Y., Pimont, F., Rigolot, E., 2007. *Pinus halepensis* architectural analysis for fuel modelling. In: Leone, V., Lovaglio, R. (Eds.), Proceedings, International Workshop MEDPINE. 3—Conservation, Regeneration and Restoration of Mediterranean Pines and their Ecosystems. Centre International des Hautes Etudes Agronomiques Méditerranéennes Editions: Montpellier, Bari, Italy, pp. 43–59.
- Chen, S.G., Ceulemans, R., Impens, I., 1994. A fractal-based Populus canopy structure model for the calculation of light interception. *Forest Ecology and Management* 69, 97–110.
- Chiba, Y., 1998. Architectural analysis of relationship between biomass and basal area based on pipe model theory. *Ecological Modelling* 108, 219–225.
- Cohen, J., Finney, M., Yedinak, K., 2006. Active spreading crown fire characteristics: implications for modeling. In: Viegas, D.X. (Ed.), V International Conference on Forest Fire Research, Coimbra, Portugal.
- Covington, W.W., Moore, M.M., 1994. Southwestern ponderosa forest structure: changes since Euro-American settlement. *Journal of Forestry* 42, 39–47.
- Cruz, M.G., Alexander, M.E., 2010. Assessing crown fire potential in coniferous forests of western North America: a critique of current approaches and recent simulation studies. *International Journal of Wildland Fire* 19, 377–398.
- Cruz, M.G., Butler, B.W., Alexander, M.E., Forthofer, J.M., Wakimoto, R.H., 2006. Predicting the ignition of crown fuels above a spreading surface fire. Part I: model idealization. *International Journal of Wildland Fire* 15, 47–60.
- Dickinson, M.B., Johnson, E.A., 2004. Temperature-dependent rate models of vascular cambium cell mortality. *Canadian Journal of Forest Research* 34, 546–559.
- Dupuy, J.-L., Morvan, D., 2005. Numerical study of a crown fire spreading toward a fuel break using a multiphase physical model. *International Journal of Wildland Fire* 14, 141–151.
- Durand, J.B., Guédon, Y., Caraglio, Y., Costes, E., 2005. Analysis of the plant architecture via tree structured statistical models: the hidden Markov tree models. *New Phytologist* 166, 813–825.
- Evans, M., Hastings, N., Peacock, B., 1993. *Statistical Distributions*. John Wiley and Sons, New York.
- Finney, M.A., 1998. FARSITE: Fire Area Simulator – Model Development and Evaluation. Research Paper No. RMRS-RP-4. United States Department of Agriculture, Forest Service Rocky Mountain Research Station, Ft. Collins, CO, USA.
- Fons, W.L., 1946. Analysis of fire spread in light forest fuels. *Journal of Agricultural Research* 72, 93–121.
- Ford, H., 1987. Investigating the ecological and evolutionary significance of plant growth form using stochastic simulation. *Annals of Botany* 59, 487.
- Fulé, P.Z., Covington, W.W., Moore, M.M., 1997. Determining reference conditions for ecosystem management of southwestern ponderosa pine forests. *Ecological Applications* 7, 895–908.
- Fulé, P.Z., Crouse, J.E., Cocke, A.E., Moore, M.M., Covington, W.W., 2004. Changes in canopy fuels and potential fire behavior 1880–2040: Grand Canyon, Arizona. *Ecological Modelling* 175, 231–248.
- Godin, C., 2000. Representing and encoding plant architecture: a review. *Annals of Forest Science* 57, 413–438.
- Godin, C., Puech, O., Boudon, F., Sinoquet, H., 2004. Space occupation by tree crowns obeys fractals laws: evidence from 3D digitized plants. In: 4th International Workshop on Functional-Structural Plant Models, Montpellier, France, pp. 79–83.
- Godin, C., Sinoquet, H., 2005. Functional–structural plant modelling. *New Phytologist* 166, 705–708.
- Goulding, C.J., Murray, J.C., 1975. Polynomial taper equations that are compatible with tree volume equations. *New Zealand Journal of Forest Science* 5, 313–322.
- Grace, J., 1997. Plant water relations. In: Crawley, M.J. (Ed.), *Plant Ecology*. Blackwell Science, Cambridge, pp. 28–50.
- Habeck, J.R., Mutch, R.W., 1973. Fire-dependant forests in the northern Rocky Mountains. *Quaternary Research* 3, 408–424.
- Hirsch, K.G., 1996. Canadian Forest Fire Behavior Prediction (FBP) System: User's Guide. Canadian Forest Service, Northwest Region, Northern Forestry Centre, Edmonton, AB.
- Hoffmann, C.W., Uoltsev, V.A., 2002. Tree-crown biomass estimation in forest species of the Ural and of Kazakhstan. *Forest Ecology and Management* 158, 59–69.
- Jenkins, J.C., Chojnacky, D.C., Heath, L.S., Birdsey, R.A., 2003. National-scale biomass estimators for United States tree species. *Forest Science* 49, 12–35.
- Jirasek, C., Prusinkiewicz, P., Moulia, B., 2000. Integrating biomechanics into developmental plant models expressed using L-systems. *Plant Biomechanics*, 615–624.
- Kang, M.Z., Cournède, P.H., De Reffye, P., Auclair, D., Hu, B.G., 2008. Analytical study of a stochastic plant growth model: application to the greenlab model. *Mathematics and Computers in Simulation* 78, 57–75.
- Keane, R.E., Reinhardt, E.D., Scott, J., Gray, K., Reardon, J., 2005. Estimating forest canopy bulk density using six indirect methods. *Canadian Journal of Forest Research* 35, 724–739.
- Krivtsov, V., Vigny, O., Legg, C., Curt, T., Rigolot, E., Lecomte, I., Jappiot, M., Lampin-Maillet, C., Fernandes, P., Pezzatti, G.B., 2009. Fuel modelling in terrestrial ecosystems: an overview in the context of the development of an object-oriented database for wild fire analysis. *Ecological Modelling* 220, 2915–2926.
- Kurth, W., 1994. Morphological models of plant growth: possibilities and ecological relevance. *Ecological Modelling* 75, 299–308.
- Kuuluvainen, T., Pukkala, T., 1989. Simulation of within-tree and between-tree shading of direct radiation in a forest canopy: effect of crown shape and sun elevation. *Ecological Modelling* 49, 89–100.



- Linn, R., Reisner, J.N., Colman, J., Winterkamp, J., 2002. Studying wildfire behavior using FIRETEC. *International Journal of Wildland Fire* 11, 233–246.
- Linn, R., Winterkamp, J., Colman, J., Edminster, C., Bailey, J., 2005. Modeling interactions between fire and atmosphere in discrete element fuel beds. *International Journal of Wildland Fire* 14, 37–48.
- Linn, R.R., 1997. Transport Model for Prediction of Wildfire Behavior No. LA13334-T. Los Alamos National Laboratory.
- Lutes, D.C., Keane, R.E., Caratti, J.F., 2009. A surface fuel classification for estimating fire effects. *International Journal of Wildland Fire* 18, 802–814.
- MacFarlane, D.W., Green, E.J., Valentine, H.T., 2000. Incorporating uncertainty into the parameters of a forest process model. *Ecological Modelling* 134, 27–40.
- Mandelbrot, B.B., 1983. *The Fractal Geometry of Nature*. W.H. Freeman and Company, New York, NY, USA.
- Mathieu, A., Cournède, P.H., Letort, V., Barthélémy, D., De Reffye, P., 2009. A dynamic model of plant growth with interactions between development and functional mechanisms to study plant structural plasticity related to trophic competition. *Annals of Botany* 103, 1173–1186.
- Mell, W., Jenkins, M.A., Gould, J., Cheney, P., 2007. A physics-based approach to modelling grassland fires. *International Journal of Wildland Fire* 16, 1.
- Mell, W., Maranghides, A., McDermott, R., Manzello, S.L., 2009. Numerical simulation and experiments of burning Douglas fir trees. *Combustion and Flame* 156, 2023–2041.
- Mell, W., McGrattan, K., Baum, H., 1996. Numerical simulation of combustion in fire plumes. In: *Twenty-sixth Symposium (International) on Combustion*. The Combustion Institute, pp. 1523–1530.
- Moore, M.M., Huffman, D.W., Fulé, P.Z., Covington, W.W., Crouse, J.E., 2004. Comparison of historical and contemporary forest structure and composition on permanent plots in southwestern ponderosa pine forests. *Forest Science* 50, 162–176.
- Morvan, D., Dupuy, J.L., 2001. Modeling of fire spread through a forest fuel bed using a multiphase formulation. *Combustion and Flame* 127, 1981–1994.
- Mutch, R.W., 1970. Wildland fires and ecosystems—a hypothesis. *Ecology* 51, 1046–1051.
- Niklas, K.J., 1986. Computer-simulated plant evolution. *Scientific American* 254, 78–86.
- Nobel, I.R., Bary, G.A.V., Gill, A.M., 1980. McArthur's fire danger meters expressed as equations. *Australian Journal of Ecology* 5, 201–203.
- Ozier-Lafontaine, H., Lecompte, F., Francois Sillon, J., 1999. Fractal analysis of the root architecture of *Gliricidia sepium* for the spatial prediction of root branching, size and mass: model development and evaluation in agroforestry. *Plant and Soil* 209, 167–180.
- Parsons, R.A., 2006. Fuel 3D: a spatially explicit fractal fuel distribution model. In: Andrews, P.L., Butler, B.W. (Eds.), *Fuels Management—How to Measure Success: Conference Proceedings*, Portland, OR, March 28–30, 2006. USDA Forest Service, Rocky Mountain Research Station. Proceedings RMRS-P-41 Fort Collins (CO), USDA Forest Service, Rocky Mountain Research Station.
- Perttunen, J., Sievanen, R., Nikinmaa, E., 1998. LIGNUM: a model combining the structure and the functioning of trees. *Ecological Modelling* 108, 189–198.
- Pimont, F., Dupuy, J.L., Caraglio, Y., Morvan, D., 2009. Effect of vegetation heterogeneity on radiative transfer in forest fires. *International Journal of Wildland Fire* 18, 536–553.
- Pradal, C., Boudon, F., Noguier, C., Chopard, J., Godin, C., 2009. PlantGL: a Python-based geometric library for 3D plant modelling at different scales. *Graphical Models* 71, 1–21.
- Prusinkiewicz, P., 2004. Modeling plant growth and development. *Current Opinion in Plant Biology* 7, 79–83.
- Pukkala, T., Kuuluvainen, T., Stenberg, P., 1993. Below canopy distribution of photosynthetically active radiation and its relation to seedling growth in a boreal *Pinus sylvestris* stand: a simulation approach. *Scandinavian Journal of Forest Research* 8, 313–325.
- Rehm, R.G., Baum, H.R., 1978. The equations of motion for thermally driven, buoyant flows. *Journal of Research of the NBS* 83, 297–308.
- Reinhardt, E., Crookston, N.L., 2003. The Fire and Fuels Extension to the Forest Vegetation Simulator. General Technical Report No. RMRS-GTR-116. Rocky Mountain Research Station, Fort Collins, CO.
- Reinhardt, E., Keane, R.E., 1998. FOFEM—a first order fire effects model. *Fire Management Notes* 58, 25–28.
- Reinhardt, E.D., Ryan, K.C., 1988. How to estimate tree mortality resulting from underburning. *Fire Management Notes* 49, 30–36.
- Reinhardt, E.D., Scott, J., Gray, K., Keane, R.E., 2007. Estimating canopy fuel characteristics in five conifer stands in the western United States using tree and stand measurements. *Canadian Journal of Forest Research* 36, 2803–2814.
- Richardson, A.D., zu Dohna, H., 2003. Predicting root biomass from branching patterns of Douglas-fir root systems. *Oikos* 100, 96–104.
- Robichaud, E., Methven, I.R., 1992. The applicability of the pipe model theory for the prediction of foliage biomass in trees from natural, untreated black spruce stands. *Canadian Journal of Forest Research* 22, 1118–1123.
- Rothermel, R.C., 1972. A Mathematical Model for Predicting Fire Spread in Wildland Fuels No. Research Paper INT-115. United States Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.
- Rothermel, R.C., 1983. How to Predict the Spread and Intensity of Forest and Range Fires No. INT-115. USDA Forest Service, Intermountain Forest and Range Experimental Station, Ogden, UT.
- Rothermel, R.C., 1991. Predicting Behavior and Size of Crown Fires in the Northern Rocky Mountains. Research Paper No. INT-438. United States Department of Agriculture, Forest Service Intermountain Forest and Range Experiment Station, Ogden, UT, USA.
- Scott, J., Burgan, R.E., 2005. A New Set of Standard Fire Behavior Fuel Models for Use with Rothermel's Surface Fire Spread Model No. General Technical Report RMRS-GTR-153. USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO.
- Scott, J.H., 1999. NEXUS: a system for assessing crown fire hazard. *Fire Management Notes* 59, 21–24.
- Shinozaki, K., Yoda, K., Hozumi, K., Kira, T., 1964. A quantitative analysis of plant form: the pipe model theory. I. Basic analysis. *Japanese Journal of Ecology* 14, 97–105.
- Sinoquet, H., Le Roux, X., 2000. Short term interactions between tree foliage and the aerial environment: an overview of modelling approaches available for tree structure–function models. *Annals of Forest Science* 57, 477–496.
- Sinoquet, H., Le Roux, X., Adam, B., Ameglio, T., Daudet, F.A., 2001. RATP: a model for simulating the spatial distribution of radiation absorption, transpiration and photosynthesis within canopies: application to an isolated tree crown. *Plant, Cell & Environment* 24, 395–406.
- Smagorinsky, J., 1963. General circulation experiments with the primitive equations I: the basic experiment. *Monthly Weather Review* 91, 99–164.
- Susott, R.A., 1982. Characterization of the thermal properties of forest fuels by combustion gas analysis. *Forest Science* 23, 404–420.
- Tyree, M.T., Ewers, F.W., 1991. Tansley Review No. 34. The hydraulic architecture of trees and other woody plants. *New Phytologist* 119, 345–360.
- Valentine, H.T., Baldwin, V.C., Gregoire, T.G., Burkhart, H.E., 1994a. Surrogates of foliar dry matter in Loblolly pine. *Forest Science* 40, 576–585.
- Valentine, H.T., Ludlow, A.R., Furnival, G.M., 1994b. Modeling crown rise in even-aged stands of Sitka spruce or loblolly pine. *Forest Ecology and Management* 69, 189–197.
- van Noordwijk, M., Mulia, R., 2002. Functional branch analysis as tool for fractal scaling above- and belowground trees for their additive and non-additive properties. *Ecological Modelling* 149, 41–51.
- Van Wagner, C.E., 1964. History of a small crown fire. *Forestry Chronicals* 40 (202–205), 209.
- Van Wagner, C.E., 1977. Conditions for the start and spread of crown fire. *Canadian Journal of Forest Research* 7, 23–34.
- Van Wagner, C.E., 1993. Prediction of crown fire behavior in 2 stands of Jack pine. *Canadian Journal of Forest Research* 23, 442–449.
- Vogel, M., Williams, F.A., 1970. Flame propagation along matchstick arrays. *Combustion Science and Technology* 1, 429–436.
- Wade, D.D., Ward, D.E., 1973. An Analysis of the Air Force Bomb Range Fire No. SE-105. USDA Forest Service, Southeast Forest Range Experiment Station, Asheville, NC.
- Weber, R.O., 1990. A model for fire propagation in arrays. *Mathematical and Computer Modelling* 13, 95–102.
- West, G.B., Brown, J.H., Enquist, B.J., 1997. A general model for the origin of allometric scaling laws in biology. *Science* 276, 122–124.