

Modeling the spatial distribution of forest crown biomass and effects on fire behavior with FUEL3D and WFDS

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Abstract

Crown fire poses challenges to fire managers and can endanger fire fighters. Understanding of how fire interacts with tree crowns is essential to informed decisions about crown fire. Current operational crown fire predictions in the United States assume homogeneous crown fuels. While a new class of research fire models, which model fire behavior with computational fluid dynamics (CFD), can be used to model fire in heterogeneous crown fuels, the potential impacts of variability in crown fuels have not yet been explored. In this study we introduce a new model, FUEL3D, which incorporates allometric theory and a simple 3D plant architecture approach to model the distribution of fuel within individual tree crowns. We then test the effects of crown fuel heterogeneity on fire behavior with a CFD fire model, WFDS, by simulating fire under a homogeneous tree crown and a heterogeneous tree crown modeled with FUEL3D, with two different levels of surface fire intensity; model output are used to estimate the probability of tree mortality, linking fire behavior and fire effects at the scale of an individual tree. 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 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 net radiative heat flux. In the higher intensity case, both cases burned readily. Differences for the homogeneous tree between the two surface fire intensity cases were minimal in nature but were dramatic for the heterogeneous tree. These results suggest that heterogeneity within the crown causes more conditional, threshold-like interactions with fire; both crown fire initiation and propagation may be more sensitive to crown fuel architecture than currently considered.

Keywords: spatial heterogeneity, crown fuels, fire behavior, plant architecture, CFD

1. Introduction

Crown fires, fires which burn through vegetation canopies, pose significant challenges to fire managers, (Albini and Stocks 1986) spreading rapidly via lofted firebrands (Wade and Ward 1973) and typically 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 have been developed for this purpose (Finney 2004, Scott and Reinhardt 2001, Reinhardt and Crookston 2003, Andrews et al. 2008, Alexander et al. 2006). These tools share a common formulation (Van Wagner 1977), which assumes

that the crown fuel to be burned consists of a single homogeneous layer of uniform bulk density and height above the ground, and that crown fire will be initiated provided that the base of this layer is heated to a sufficient temperature. Similarly, models used to predict fire induced tree mortality assume a homogeneous crown volume extending from the crown base to the top of the tree and intersect that volume with a predicted scorch height (Van Wagner, 1973, Ryan 1988, Reinhardt and Ryan 1988, Ryan 1998, Reinhardt et al. 2001, Keyser et al. 2006); the likelihood that a tree will be killed increases with the proportion of the crown volume burned.

The assumption of a homogeneous crown layer is thus a central component in current models used to predict the initiation of crown fires and tree mortality arising from fires. Implicit in the assumption of homogeneity is that variability at finer scales is unimportant to fire behavior. While it may be reasonable to assume a homogeneous crown layer in forest types characterized by dense, continuous trees of very similar size and age, typified by the stands used in Van Wagner's analysis (Van Wagner 1964, Van Wagner 1968), such an assumption is increasingly tenuous when applied to stands characterized by variability in size and numbers of trees. At present Van Wagner's model is used in operational models for all forest types, regardless of the composition, structure and stocking of the stand; it is likewise applied in stands that have been thinned or affected by disease (Reinhardt and Crookston 2003). To date, however, the potential implications of crown fuel heterogeneity for crown fire initiation and tree mortality have not been explored.

2. Objectives

In this investigation we use modeling to explore the effect of heterogeneity in bulk density within a tree crown on fire behavior. Using a spatially explicit fuel distribution model, FUEL3D, we simulate 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.

3. Methods

Overview of the FUEL3D model

FUEL3D is a static, stochastic, structural plant model designed to characterize how biomass within a tree crown is distributed in space. FUEL3D is designed primarily to provide a means by which typical stand inventory data, such as tree heights, diameters and other basic measurements, can be used to develop detailed and spatially explicit descriptions of crown fuels and their characteristics for inputs to advanced fire behavior models. 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, Chiba 1998) and a recursive branching algorithm. **Figure 1** presents a conceptual diagram of the FUEL3D model. Branching geometry and architecture, and variability in that architecture, are parameterized from field measurements. FUEL3D retains variability observed in input data by drawing from field data-driven probability distributions throughout the architectural simulation. Although

FUEL3D can be used to model a broader range of plants, such as shrubs, grasses and deciduous trees, these developments are still in preliminary stages. In this study we utilize FUEL3D to model coniferous trees.

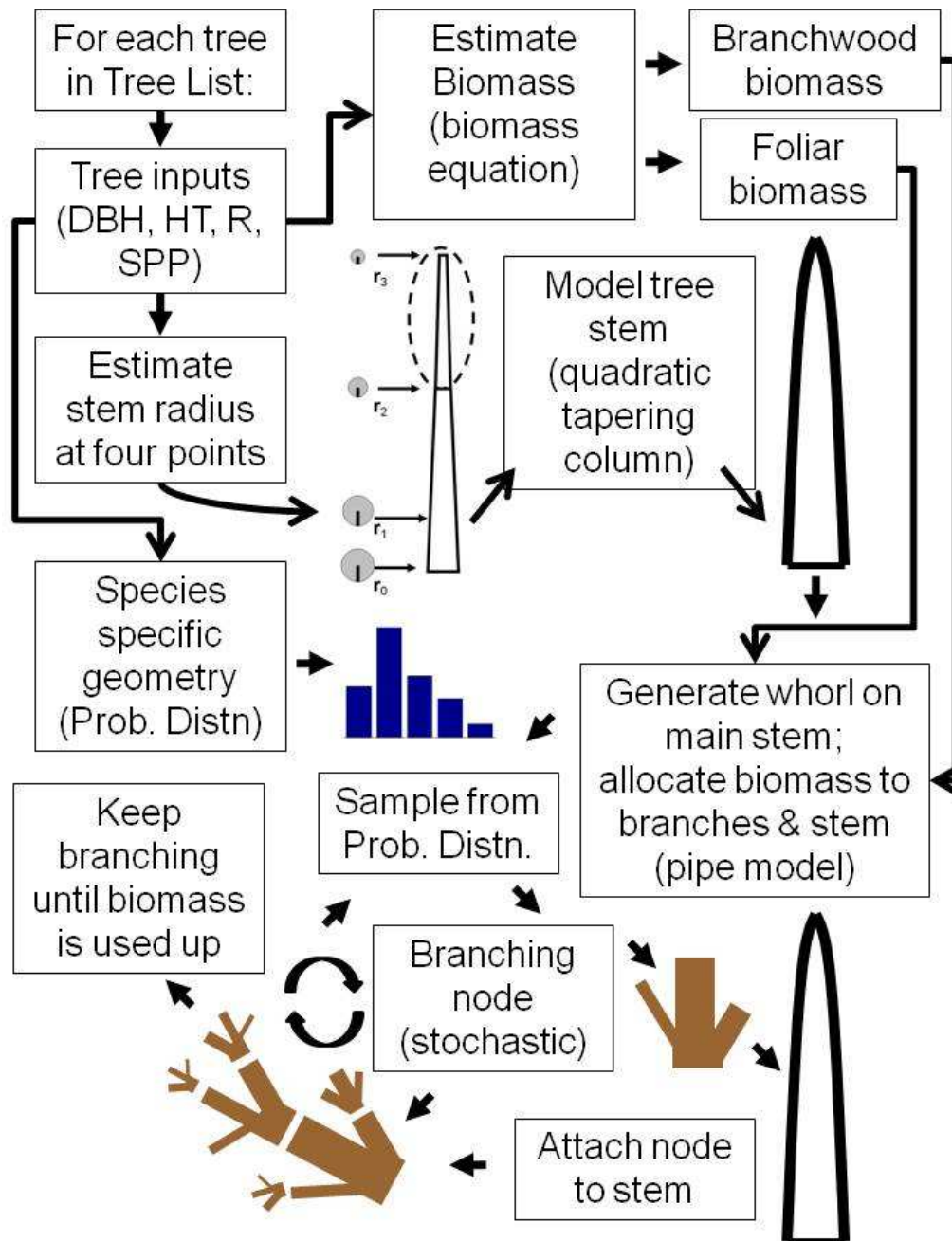


Figure 1. Schematic diagram illustrating the process by which FUEL3D models fuel.

The primary output of the FUEL3D model is a spatially explicit database which stores primitive geometric structures representing biomass components within a tree crown (e.g. cylinders, planar polygons etc.), tracking 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) 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 transcending a range of spatial scales.

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

Symbol	Individual Tree Measurements from Inventory
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
Symbols used in FUEL3D model	
$A_{breast\ height}$	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 nth 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
l_o	initial segment length
l	a segment length
γ	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
ρ	Wood density, assumed constant throughout tree.
ρ_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

FUEL3D begins with modeling the tree bole. The tree bole is modeled as a quadratic polynomial tapering column (Goulding and Murray 1975) of the form $r_z = p_1 z^2 + p_2 z + p_3$ (Eqn 1), 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 by fitting the polynomial to four points: r_0 , (radius at tree base, calculated from dbh and species specific bole taper equations (Alemdag and Honer 1977)), r_1 , (radius at breast height (measured)), r_2 , (radius at base of live crown), calculated from the cross sectional area at the base of the crown, $A_{\text{crown base}}$ which is calculated as $A_{\text{crown base}} = R A_{\text{breast height}}$ (Eqn 2) 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. 1994). The fourth point, r_3 , is radius at the tip of a branch, from field data, and assumed to be radius at the top of the tree. 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.

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.

FUEL3D distributes biomass above the base of the live crown by first constructing a series of whorls, or branching nodes, along the bole, and then building the branches one at a time. Foliar biomass and branchwood biomass quantities are allocated to each branch on the basis of cross sectional area. Inter-whorl section lengths are obtained from a distribution parameterized from field data. At each whorl, a portion of the cross sectional area (and corresponding biomass) is diverted laterally to branches, while the remainder continues farther up in the main stem of the tree.

Both whorls along the bole, and branching nodes within the branches, are stochastically generated by sampling from probability distributions parameterized from field measurements; different probability distributions govern different aspects. The number of child segments is a discrete variable sampled from histograms binned from field data, while the proportion of cross sectional area, and angles that child segments start at relative to their parent segment are continuous variables drawn from a Beta probability distribution (Evans et al. 1993). Incorporating these probability distributions within the FUEL3D model ensures that variability observed within field data is preserved in model output.

Each branch is modeled with a recursive (self-referencing) algorithm, similar to fractal tree and root structure 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. 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. Foliar biomass is expended and modeled as part of the branch after a diameter threshold is reached. 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.

Parameterization for Ponderosa pine

Branching architecture characteristics, (number of child branches, angles, diameters and lengths) were parameterized from field data collected at Ninemile on the Lolo National Forest near Missoula, Montana in July 2007. A larger data set collected from destructive sampling of whole trees between 2000 and 2003, known as the Crown Fuels Study (CROWNFUELS) (Keane et al. 2005, Reinhardt et al. 2007) provided additional data that was helpful in the development of a prototype version of the FUEL3D model (Parsons 2006). In the 2007 field data collection, ten Ponderosa pine trees were selected from the same stand and were felled using a restraining system so crowns would not be damaged by felling. For each tree, total height, diameter at breast height, and height to, and diameter of, 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 bole. Similar measurements were made within branches to capture geometry at higher branching orders, based on a subsample of every third branch. All measurements were recorded with branch order to facilitate analysis of changes in architecture with branch order. Geometry of foliage clumps was characterized with additional sub sampling. Finally, digital images were taken of each subsampled branch, with and without foliage, with a metric ruler for scale, to capture other aspects of branch geometry; additional measurements were made upon these images post field using image processing software. Altogether 388 first order branching nodes and 687 higher order branching nodes were described. Field sampled parameters are presented in **Table 2**.

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						
Empirical constants and relationships								
r_3	1	Minimum branch radius (mm)	2.1					
L_T	2	predicted total branch length $L_T=0.6369d^{0.8909}$, $R^2=0.968$						
Continuous variables modeled with beta distribution			min	max	v	w		
L_i	1	Inter-whorl length, along main stem, for a whorl, i	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		
Discrete variables, sampled from empirical histograms								
$m_{first\ order}$	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

Simulation of a spatially variable tree crown

Using the field data parameters and modeling process described above, we used FUEL3D to simulate the distribution of biomass within the crown of an individual

ponderosa pine (*Pinus ponderosa*) tree, with a 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 2.5m. These basic tree measurements are used to calculate biomass quantities to be distributed in space. Crown biomass was estimated using the equation provided by Brown (1978), which calculates total crown biomass (which includes both foliage and branchwood) as $M_c = e^{(2.2812 \ln(d) + 1.5098(R) - 3.0957)}$ (Eqn 3); foliage is then calculated as a proportion of that total as $p_{fol} = 0.558e^{(-0.4075 \text{dbh})}$ (Eqn 4), where M_c is the biomass within the crown (excluding stem), R is the crown ratio, dbh is tree diameter at breast height in inches, and output biomass is measured in pounds. Using the values for our test tree above, this yielded a total crown biomass of 99.233 Kg of fuel of which foliar biomass was 34.435 Kg.

The output was a spatially explicit database of discrete fuel elements recording the positions and attributes of all woody components and foliage. A visualization of this tree is presented in **Figure 2**. From this database we extracted only those elements which < 6 mm in diameter as these smaller diameter, thermally thin material dominate fire behavior due to their high surface area to volume ratio, and rapid interaction with incident heat fluxes. Woody material within the simulated crown within this diameter range summed to 10.471 Kg, which with the foliage, produced a total of 44.9060 Kg of thermally thin fuel within the simulated crown.

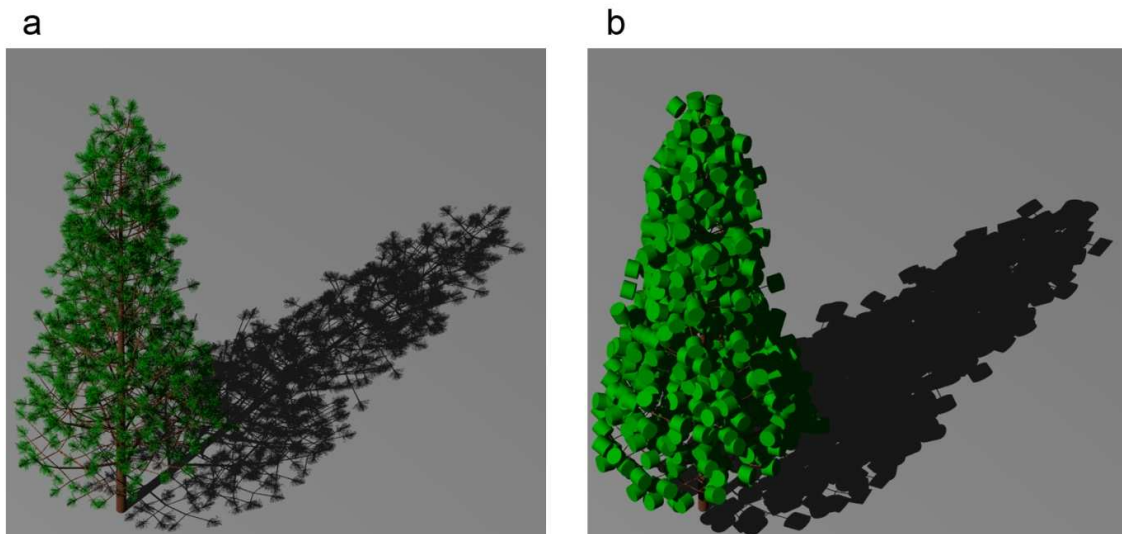


Figure 2. Example visualizations of a tree simulated with the FUEL3D model. The figure at left (a) shows a conifer tree with explicit spatial detail to the level of individual needles. For most purposes, this representation is unwieldy; for this reason, groups of detailed smaller structures can be represented with larger simple bounding volumes, such as cylinders, as shown at right (b).

The set of thermally thin fuel elements within the database was then summarized to cells 0.25m on a side for input into the WFDS model (**Figure 3**). 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 17700 kg^{-1} (Susott, 1982), surface area to volume ratio constant at 4000 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 (Mell et al., 2009). Fuel moisture content was constant at 90% on a dry weight

basis. The only form of variability considered in our 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.

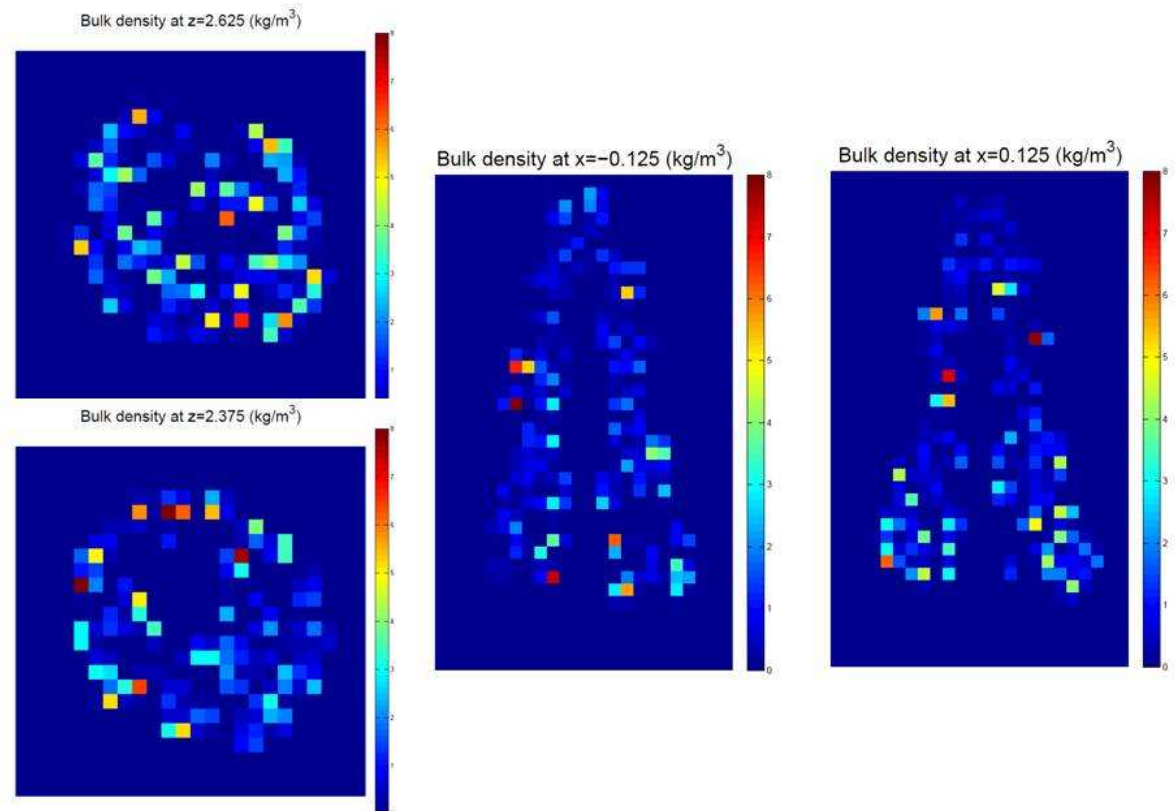


Figure 3. Distribution of fuel bulk density of thermally thin material ($\leq 6\text{mm}$ in diameter) within the spatially variable tree modeled in this study, summarized to 0.25m cells. Figure shows two horizontal slices (left) and two vertical slices (right).

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 (1.5m) and extended to the same height (10 m) as the tree modeled above. This volume was filled with the same total amount of 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 kg/m^3) while the spatially variable crown had a range of bulk densities.

WFDS Model

The Wildland-Urban Interface Fire Dynamics Simulator (WFDS) model (Mell et al., 2009) 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 x 1500 m for the simulation of Australian grassland fires (Mell et al. 2007).

Numerical Experiment

We tested the effect of spatial distribution of biomass within the crown of an individual tree on fire behavior with the WFDS model (Mell et al. 2009). Our simulation experiment compared two different tree crowns: a homogeneous crown, (H), with a constant bulk density of thermally thin fuel, and a spatially variable crown (V), with the same total fuel quantity and gross dimensions as the homogeneous case above, but modeled with FUEL3D. 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, VL, HH, VH). Our numerical experiment is described in more detail below.

The spatial domain used in these simulations measured 24 meters by 24 meters by 20 meters. 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 x 32 by 80 cells and run on 9, 64 bit processors. Total simulation time was 180 seconds; with the nine processors, real time duration of each simulation averaged 2 hours and 20 minutes.

The surface fire was simulated as user-prescribed advancing flaming front with a constant forward spread rate (0.1 m/s) 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 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

$$\sum_j \int \nabla q_{rad} dV_j$$

Eqn 5

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

Linking fire behavior and fire effects

For both trees we assessed the probability that the tree would be killed by the fire, using the equation:

$$P_{mort} = 1 / \left(e^{(-1.941 + (6.315(1 - e^{-w})) - (0.000535s^2))} \right)$$

Eqn 6

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 inches (16 mm) based on observed bark thickness relationships (Reinhardt and Keane 1998).

4. Results

Differences in the spatial configuration of fuels within the tree crown resulted in substantial differences in fire behavior (**Table 3, Figure 4**); the nature and magnitude of these differences, however, varied with the intensity of the surface fire below the tree crowns (**Figure 5**). 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 (**Figure 5**). Similarly, total net radiative heat transfer 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, Figure 5**). 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**).

Table 3. Summary of Fire Behavior Simulation Outputs.

Label	Solid fuel, Kg				Total Net Radiative heat Transfer, KW			P(mort)
	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

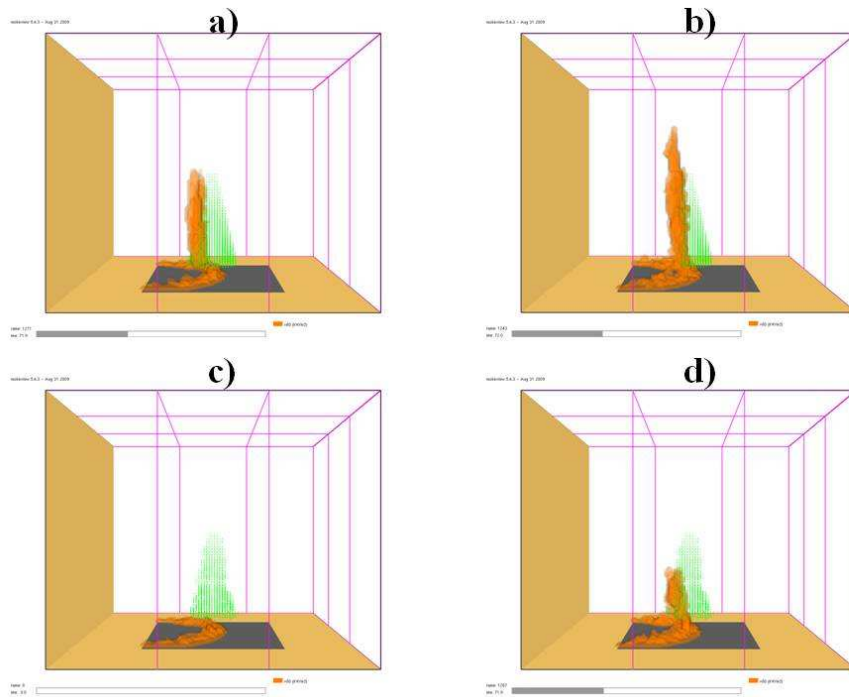


Figure 4. Comparison of four different numerical fire behavior simulations with the WFDS model, at the same point in time($t=72$ s): A) homogeneous tree, lower surface fire intensity (case HL), B) Homogeneous tree crown, higher surface fire intensity (HH), C) Variable tree crown, low intensity (VL), and D) Variable tree crown and high intensity (VH). The total amount of fuel was identical for all four simulations.

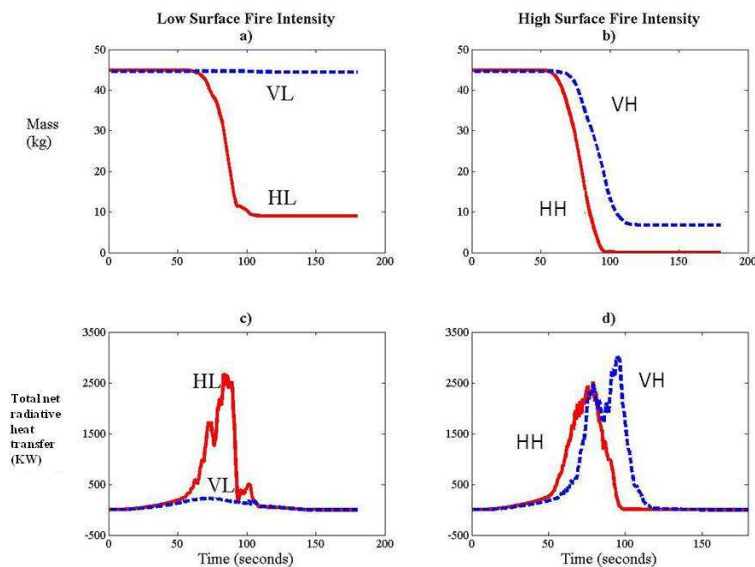


Figure 5. Comparison of outputs from four different numerical fire behavior simulations with the WFDS model. Red solid lines show outputs for the homogeneous tree crown while blue dash lines show outputs for the spatial variable tree crown produced with the FUEL3D model. Top two figures compare solid fuel consumption between the low surface fire case and the higher intensity surface fire case. Bottom two figures compare net radiative heat flux between the low surface fire case and the higher intensity surface fire case. The total amount of fuel was identical for all four simulations.

5. Discussion

FUEL3D represents a compromise between more elaborate modeling approaches, with more advanced theory, and simpler approaches which are better suited to practical use. FUEL3D uses a pipe model based recursive branching algorithm that is similar to many theoretical models; by building the tree stem first and using this algorithm at each branch, rather than building the whole tree with that algorithm, FUEL3D retains the flexibility to represent individual measured trees. This improves its application with existing forestry inventory data and associated models.

Models have been developed which represent wildland fuels for different purposes, including fire behavior fuel models (Anderson 1982, Scott and Burgan 2005), which provide inputs to current operational fire behavior models, fuel loading models (Sikkink et al. 2009), which estimate fuel quantities for fire effects calculations, and fuel classifications (Ottmar et al. 2007, Riccardi et al. 2007). The principal difference between FUEL3D and these fuel descriptions is that it is spatially explicit, capable of quantifying variability in different wildland fuel characteristics across a spectrum of spatial scales. This capability will facilitate improvements in our understanding of fundamental fuels science. By building fuel beds from fine scale components of individual trees and other fuel components, loss of relevant detail, and potential scale-dependent pitfalls associated with fuel classifications (e.g. Sandberg et al. 2001) can be avoided. At present there is no way that fundamental wildland fuel properties, such as the size class distribution of particles or distribution of fuel density within a tree crown can be easily calculated. FUEL3D provides a means of estimating some of these properties from the simulated structure. More work is needed to extend the model to a broader range of species.

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 net radiative heat flux, 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.

Our numerical experiment has implications for fire behavior modeling, and particularly, for modeling crown fire behavior. The homogeneous tree crown burned faster and more consistently than the spatially variable crown. Operational fire models in the United States have significant issues with modeling crown fire (Cohen et al. 2006) and tend to underestimate crown fire spread rates (Cruz and Alexander 2010). But, even if the underlying physical processes were modeled more accurately, an assumption of homogeneous fuels might still result in inaccurate crown fire 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. This conditional nature of fire spread has been noted previously (Cohen et al. 2006) and poses challenges for modeling crown fire behavior. For some aspects of crown fire behavior, 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.

Fuel modeling is a rapidly evolving field. Rapid advances in computer science and in plant architecture modeling are advancing our capabilities to address the mechanisms by which wildland fuels influence and interact with fire. Using a plant architecture approach, researchers have applied plant architecture modeling to description of wildland fuels and have used simulated plants as inputs to HIGRAD-FIRETEC, a CFD fire behavior model (Caraglio et al. 2007; Krivtsov et al. 2009). Our study complements these efforts by modeling fire and fuel interactions at a finer scale (0.25m cells as opposed to 2m cell resolution). Altogether, these developments pose many advantages. First, detailed plant modeling provides a quantitative description of fuels that can actively inform, and 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. 2006, Pimont et al. 2009). Second, this approach provides a quantitative means of linking fire behavior and fire effects. In this study we linked fire behavior and fire effects, at the scale of an individual tree, by using outputs of a CFD fire behavior model in conjunction with an empirical statistical model of tree mortality, primarily on the basis of crown fuel consumption. 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.

Finally, linking detailed fuel models with detailed fire behavior models will provide us with quantitative guidance for fire and fuel management decision support. Current fire management strategies and policy emphasize modification of the fuels, through fuel treatments such as thinning and prescribed burning. A more detailed modeling approach will improve our capability to evaluate different treatment alternatives.

6. References

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