# FUEL3-D: A Spatially Explicit Fractal Fuel Distribution Model

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***Abstract***—*Efforts to quantitatively evaluate the effectiveness of fuels treatments are hampered by inconsistencies between the spatial scale at which fuel treatments are implemented and the spatial scale, and detail, with which we model fire and fuel interactions. Central to this scale inconsistency is the resolution at which variability within the fuel bed is considered. Crown fuels are characterized by clumps of fuel separated by gaps between needles, between branches, and between trees. A growing body of evidence suggests that this variability plays an important role in how fire spreads. A new system currently in development for representing fuels with higher detail, called FUEL3-D, is presented. FUEL3-D is designed to both facilitate fundamental fuel and fire science research and to provide detailed guidance to managers in the design and evaluation of fuel treatments. Unlike existing fuel models that do not deal with spatial structure or variability within the fuelbed, FUEL3-D represents fuels with spatially explicit detail; individual branches on individual trees are resolved and quantified using fractal geometry and allometric relationships. Fuels can be summarized to 3-D pixels, at any scale, as input to advanced physical numerical fire behavior models such as FIRETEC and WFDS. FUEL3-D can thus be used to represent fuels before and after treatment with much greater detail than has been possible before. Model development, preliminary validation against destructively-sampled crown fuels data sets, and current research inquiries are discussed.*

## Background

Current fire management practices and policy emphasize implementation of fuel treatments, such as thinning and prescribed burning, that seek to modify future fire behavior by reducing or altering the fuel bed in some way. A common objective of many fuels treatments is to reduce the likelihood of a fire spreading from surface fuels, such as litter and fine woody debris, to the forest canopy. Fuel treatments must generally be implemented at one time, and actually tested (by a wildfire passing through or near them) at a different time. As substantial resources must be committed to carry out fuel treatments, and conditions at the time the treated area burns are unknown, fuel treatment assessments rely heavily on predictions from computer models. The accuracy of predictions from such models is dependent on the detail with which they represent the main components of the problem, namely, wildland fuels and their interactions with fire.

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 and Busing and Mailly 2004 for reviews of several such models, respectively). A common

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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 1987, Pukkala et al. 1993). Such representations are limited to particular scales because detail within the tree crown is not modeled. A much more accurate approach represents plants as fractal objects (Mandelbrot 1983, Godin 2000) and model plant architecture in detail, sometimes extending as far as individual branches, twigs and leaves (Berezovskava et al. 1997, Ozier-Lafontaine et al. 1999, Richardson and Dohna 2003, Godin et al. 2004). Such approaches are particularly relevant to representation of canopy fuels because they successfully capture the natural pattern of clumps of fuel separated by gaps, such as those between needles and between branches.

The clumped nature of wildland fuels is important to fire behavior because propagation of fire is a fundamentally fine scale, spatial process, dependent on the size, shape, composition and arrangement of fuel particles (Burrows 2001) and, particularly, distance between fuel particles (Fons 1946, Vogel and Williams 1970, Weber 1990, Bradstock and Gill 1993). Current management tools used to predict fire behavior, such as BehavePlus (Andrews 2003) and FARSITE (Finney 1998) do not deal with spatial relationships within the fuel bed and cannot be used to reliably assess transitional fire behaviors, such as the change from surface fire to crown fire, or fire-atmosphere interactions that strongly influence the initiation of rapid and intense "blow-up" behaviors which may pose great threats to fire fighter safety (Rothermel 1991, Potter 2002). Fuel treatments can only be assessed with such models as a comparison of average conditions (e.g., Van Wagtendonk 1996). This is problematic because the complex and dynamic nature of fire-fuel and fire-atmosphere interactions may result in cases in which the average conditions either do not actually occur (such as mean crown base height in a two storied tree stand) or do not result in average fire behavior.

In recent years more advanced physics-based, numerical fire behavior models have emerged, such as FIRETEC (Linn et al. 2002, Linn and Cunningham 2005), and WFDS (Mell et al. 2005) that consider spatial variability within the fuel bed, fire-fuel interactions and fire-atmosphere interactions. The detail with which these models address fundamental drivers of fire behavior, as well as the underlying physics basis of the models, facilitates robust prediction of fire behavior and related analyses of fuel treatments at multiple scales.

One of the key limitations in the application of these models is that they require fine scale spatially explicit fuels inputs that are difficult to directly measure in the field, such as 3-D cells describing the distribution of fuel density within a tree. While the fire behavior models are very sophisticated in their treatment of the physics of fire spread and heat transfer, fuels information for wildland fuels of commensurate detail is extremely rare or non-existent. At present no procedures exist by which fuels data measured in the field can be used to develop these inputs or test the accuracy with which fuels are represented. Perhaps even more importantly, no tool exists by which the fundamental properties of wildland fuels can be assessed, quantified and evaluated as to their importance across a range of spatial scales. Wildland fire science will not be able to take full advantage of the advancements that have been made in fire modeling until these knowledge gaps are addressed.

One component of fuel treatment assessments that has not received much attention is the change in microclimate resulting from the treatment. The size, density and geometry of plants affects solar radiation at the forest floor (Reifsnyder and Lull 1965, North 1996, Govaerts and Verstraete 1998) and the interception of rain by the canopy (Helvey and Patric 1965), which both influence fuel moisture (Fosberg and Deeming 1971, Nelson 2002). The canopy structure also influences winds within a stand (Jensen 1983, Oke 1978, Brandle 1980). Fuel treatments may thus result in significant feedback relationships with the microclimate, which may alter the future behavior of fire within a stand in unexpected ways. At present we are greatly limited in our ability to assess the nature and magnitude of these effects.

# Objectives

In this paper I introduce a spatially explicit fuel model called FUEL3-D, which can be used to represent fuels in great detail, both as discrete branches and as 3-D cells. This model represents a new concept in fuel modeling, in which fuel beds are described as a collection of discrete elements such as individual trees and branches within trees. FUEL3-D can be used to provide inputs to detailed numerical fire behavior models that account for spatial relationships within the fuel bed and are thus more sensitive to fuel treatments than current operational fire models.

I describe preliminary parameterization for ponderosa pine crown fuels based on destructively sampled crown fuels data and present results of preliminary validation analyses of biomass quantities against independent validation data. I then demonstrate two ways in which fine scale representations of fuels might provide insights relevant to fuel treatment assessments. First, I demonstrate how spatial relationships within the fuel bed influence fire behavior using a three-dimensional physical fire behavior model, WFDS (Mell et al. 2005). Second, using ray-tracing procedures I demonstrate how the spatially resolved structure of wildland fuels can be used to simulate the influence of the forest canopy on light dynamics at the forest floor, an important component of surface fuel moisture dynamics as well as vegetative response to fuel treatments. I conclude with discussion of how modeling fuels at fine scales fits into the larger picture of fire management.

# Methods

## *Parameterization of the FUEL3-D Model for Ponderosa Pine*

As the precise number, size and positions of individual branches composing the crown of an individual tree will generally never be known, it is necessary to simulate this structure. This is done on the basis of relationships identified from field data describing biomass quantities and geometry within the crown.

**Field Data and Analysis**—Detailed crown fuels data were collected through a destructive sampling crown fuels study in five locations in the western United States in 2000 and 2002 (Scott and Reinhardt 2002). In each study location, field crews systematically measured, removed, dissected and weighed individual branches for each tree in five stands destructively sampled between 2000 and 2002 (Scott and Reinhardt 2002). Tree level measurements included height, height to crown base, health status, canopy class (dominant, codominant etc.), coordinates of the tree stem and diameter at breast height (1.35 m, DBH). Branch level measurements included branch basal diameter, height on bole, angle from vertical, total length, width, and weight, separated out by component (woody vs. foliage, live or dead, etc.).

Woody fuels were separated and weighed by fuel moisture lag time size classes, i.e. 1 hour, 10 hour (Fosberg and Deeming 1970). I used tree and branch data measured for ponderosa pine (*Pinus ponderosa*) trees in a dense, single storied stand at the Flagstaff, Arizona field site in this initial development and testing of the FUEL3-D model. Of the original 85 trees, 7 trees with no individual branches, such as broken snags, were excluded from analysis, resulting in a data set of 78 trees and a total of 2207 individually measured branches. The trees were mostly codominant and intermediate trees with diameters ranging from 2.6 to 38.4 cm (mean 17.2 cm) (Figure 1). The majority (80%, 62 trees) of this data was randomly selected for model-building (to develop empirical relationships used in the model), and the remainder (20%, 16 trees) was withheld for validation. An additional 16 ponderosa pine trees measured at the Ninemile, Montana field site for the same study were used to assess how well relationships identified for the Flagstaff data could be applied to ponderosa pine trees sampled at other locations.

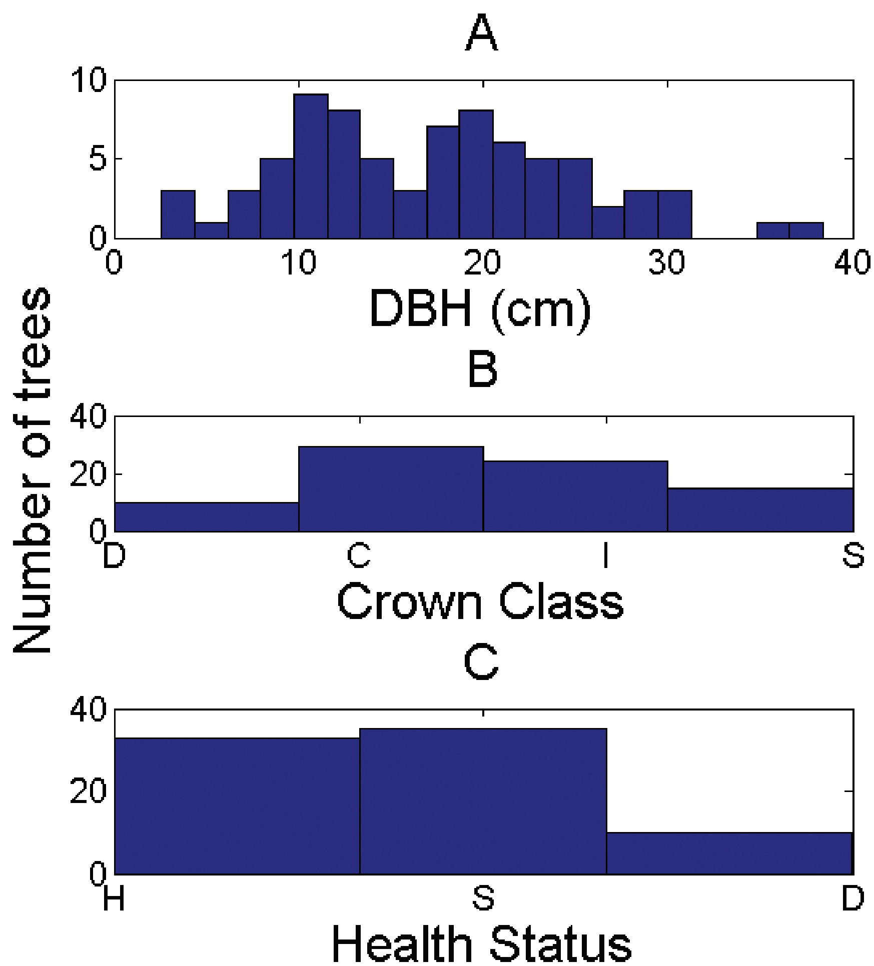


**Figure 1**—Three plots showing properties of data for the 78 ponderosa pine trees used in this study. All data used were from the Flagstaff field site: A) diameter distribution: B) Crown class distribution: D=Dominant, C=Codominant, I=Intermed, S=Suppressed. C) Health Status: H=Healthy,S=Sick,D=Dying

I supplemented this main data set with additional data collected in 2004 and 2006 in Montana. These data sets included measurements of angles between sub-branches, lengths and diameters of sub-branches as proportion of parent branches, and weights and dimensions of individual clumps of needles. This data in combination with the more extensive crown fuels study data described above provided information adequate for modeling sub-branches and distribution of biomass within a branch.

Using the model-building data I used non-linear regression procedures to predict the total branch biomass, and total foliar biomass for a branch as a function of basal branch diameter. I then used maximum likelihood estimation procedures to fit theoretical Weibull probability density functions (Grissino-Mayer 1999) describing the branch size class distribution of individual branches as a proportion of tree diameter at breast height (DBH) (Figure 2). The Weibull distribution is a flexible continuous positively skewed distribution described by the probability density function

$$f(y) = \left( c y^{(c-1)} / b^c \right) e^{(-(y/b)^c)} \qquad [1]$$

for the range $0 <= y < \infty$ , scale parameter, b and shape parameter, c. I assessed model fit for branch size distributions with the Komologorov-Smirnov (K-S) test. Additional analyses (not presented here for the sake of brevity) assessed relationships between the position and orientation of the base of a branch along the tree stem and set upper limits for the total length and width of each branch, all on the basis of branch basal diameter. A summary of parameters used to describe and model ponderosa pine is presented in Table 1.

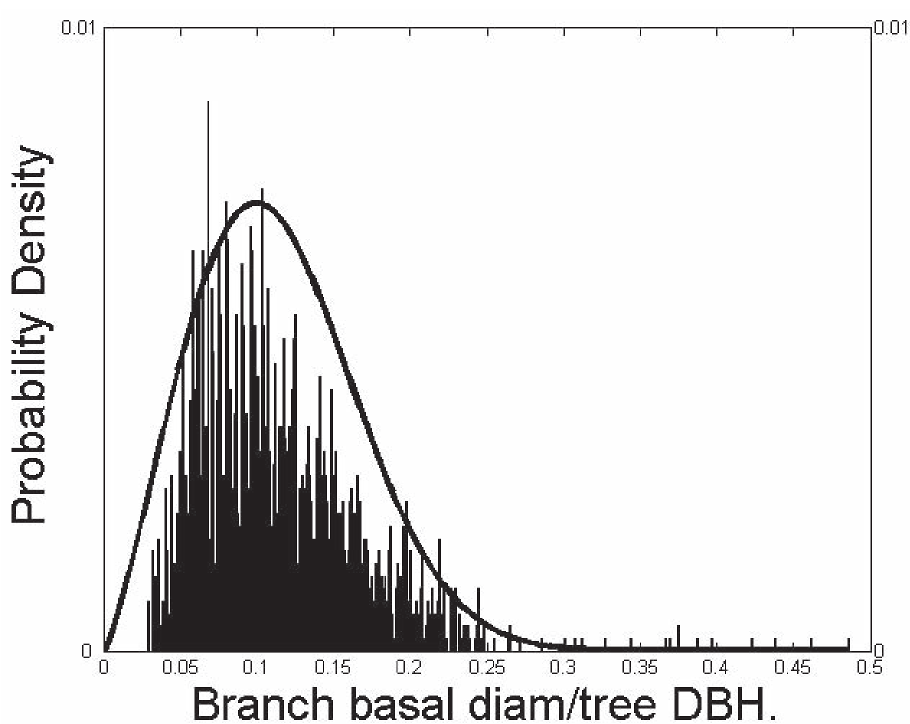


**Figure 2**—Distribution of branch basal diameters, as proportion of tree diameter at breast height, for 62 ponderosa pine trees destructively sampled near Flagstaff, Arizona. Smooth line shows theoretical distribution fitted on this data.

**Table 1**—Empirical relationships and parameters used to model ponderosa pine crowns.

| Dep. var. (abbrev), units | Indep. var. (abbrev), units | Function type | Equation | Fit |
|---|---|---|---|---|
| **Allometries** | | | | |
| Branch diameter size class distribution[a] | | Weibull pdf. | $f(y) = (cy^{(c-1)} / b^c)\, e^{(-(y/b)^c)}$<br>b = 0.128<br>c = 2.285 | K-S 0.06<br>p-value 0.0002 |
| Total branch biomass(TB), g | Branch basal diameter(BD),cm | Power $Y = ax^b$ | $TB = 27.17 * BD^{2.77}$ | $R^2 = 0.96$ |
| Branch foliar biomass (FB), g | Branch basal diameter(BD),cm | Power $Y = ax^b$ | $FB = 11.15 * BD^{2.36}$ | $R^2 = 0.92$ |
| **Geometry** | | | | |
| Total branch width (BW), m | Total branch length (BL,m) | Linear Y = ax | BW = 0.50 * BL | $R^2 = 0.69$ |
| Total branch length (BL), m | Branch basal diameter(BD),cm | Power $Y = ax^b$ | $BL = 0.47*BD^{0.99}$ | $R^2 = 0.77$ |
| Angle between branches, degrees | NA | Random, normal pdf. | Mean = 77 stdev = 9 | |

[a] Branch diameter distribution modeled as a proportion of tree diameter, so y = Branch basal diameter / tree d.b.h. This accounts for the increase in branch diameters as trees get larger.

**Simulation of Tree Crowns**—Simulation of a tree begins with a measurement of DBH. This is used to predict the size class distribution of branch basal diameters on the basis of analysis described above. Individual branch basal diameters are then sampled from this distribution until the sum of the cross sectional areas of the branches equal the tree cross sectional area. This relationship, first observed by Leonardo da Vinci and later applied in the pipe model theory (Shinosaki et al. 1964), has been shown to be true for a wide range of tree species and is a common basis in fractal models of plant structure (Berezovskava et al. 1997, Ozier-Lafontaine et al. 1999, Enquist 2002). For each branch basal diameter total branch biomass and foliar biomass quantities are then predicted using empirical functions described above. At this point each branch is defined in general terms but has no structure of sub branches.

The structure of sub branches which comprises the total branch is modeled as a series of frustums of a right circular cone, described by two vertices defining the position of the end points, and the radii at each end perpendicular to the line connecting the vertices (Figure 3). The branching structure is assembled using a static fractal model approach (e.g., Ozier-Lafontaine et al. 1999), described only briefly here. An initial segment is defined which represents the first part of a branch up to the point where sub branches form. The dimensions of this branch, along with geometric parameters describing the number of child branches and angles between them are used as the “seed” in a recursive function, common to numerous fractal tree models (Berezovskava et al. 1997, Niklas 1986). The effect of the recursive function is to continue

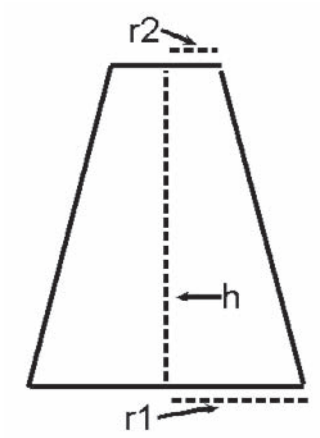


**Figure 3**—Planar view of a frustum of a cone, defined by length h, large radius R, and small radius r. The frustum of a cone is the basic building block for branches within the FUEL3-D spatial fuel model.

branching until some predefined end condition is met. In this manner each branch extends itself, splits into smaller branches, which themselves split into smaller branches, and so on (Figure 4). The position of each segment in 3-D space, dimensions and orientation and other attributes are written to a list for future use. In this initial configuration of the model branching was stopped when the distal radius of the segment was small enough to be considered a terminal, which represents a clump of needles. A terminal is defined in space as a frustum of a cone but also has additional attributes describing the total number of needles, surface area, foliar biomass etc. For extremely detailed simulations (typically only within a small area) it is possible to replace each terminal with a series of smaller objects. In this manner it is possible to represent detail down to the level of individual needles if desired.

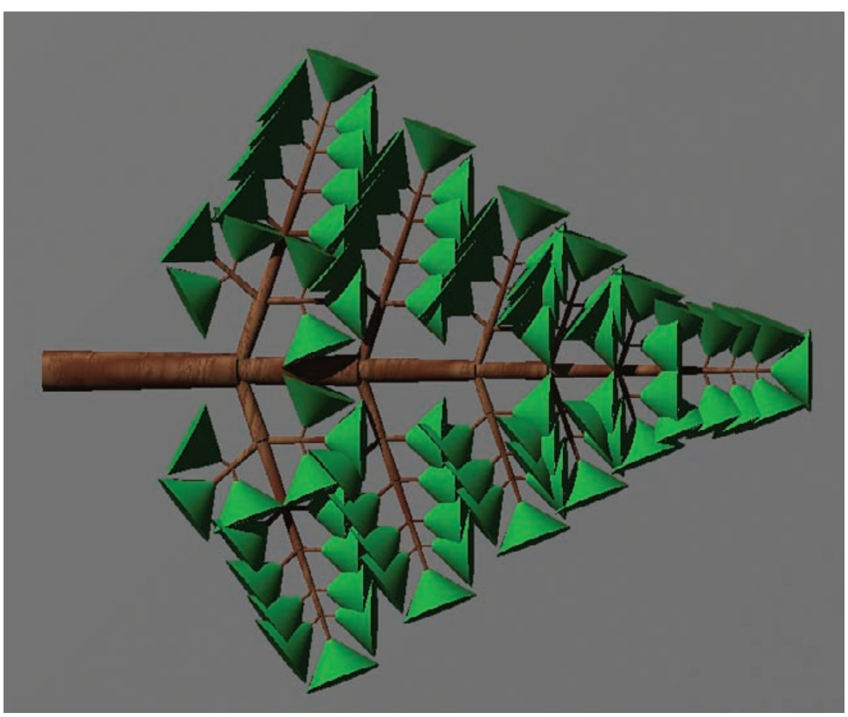

**Figure 4**—A simulated branch with sub-branches generated with FUEL3-D.

**Summarization to 3-D cells**—In order to use the fuels data defined as discrete objects in the numerical fire behavior models it is necessary to convert the data to values associated with three-dimensional grid cells (Figure 5). This is accomplished by slicing each branch segment, perpendicular to its main axis into a number of circular cross sections. Each circle is "clipped" along the line of intersection between the plane within which it lies and each of the applicable planes which constitute the limits of the 3-D cell. The area of the resulting, possibly irregular, polygon is stored off in a list. All of these areas are then numerically integrated to calculate the volume of that branch that lies within the particular cell. This procedure is repeated for each cell and for all branch segments. Parts of a branch segment that are cut out of one cell will be accounted for in an adjacent cell. In this manner the total quantities are preserved across whatever spatial scale is desired.

**Comparison With Validation Data**—Comprehensive validation of a complex model often requires a large number of tests; as the FUEL3-D model is still in active development validation efforts are ongoing. I compared the measured total crown biomass, for the two independent validation sets, against quantities simulated with FUEL3-D (Figure 6). The modeled relationships used in testing were all derived from the Flagstaff model building data set.

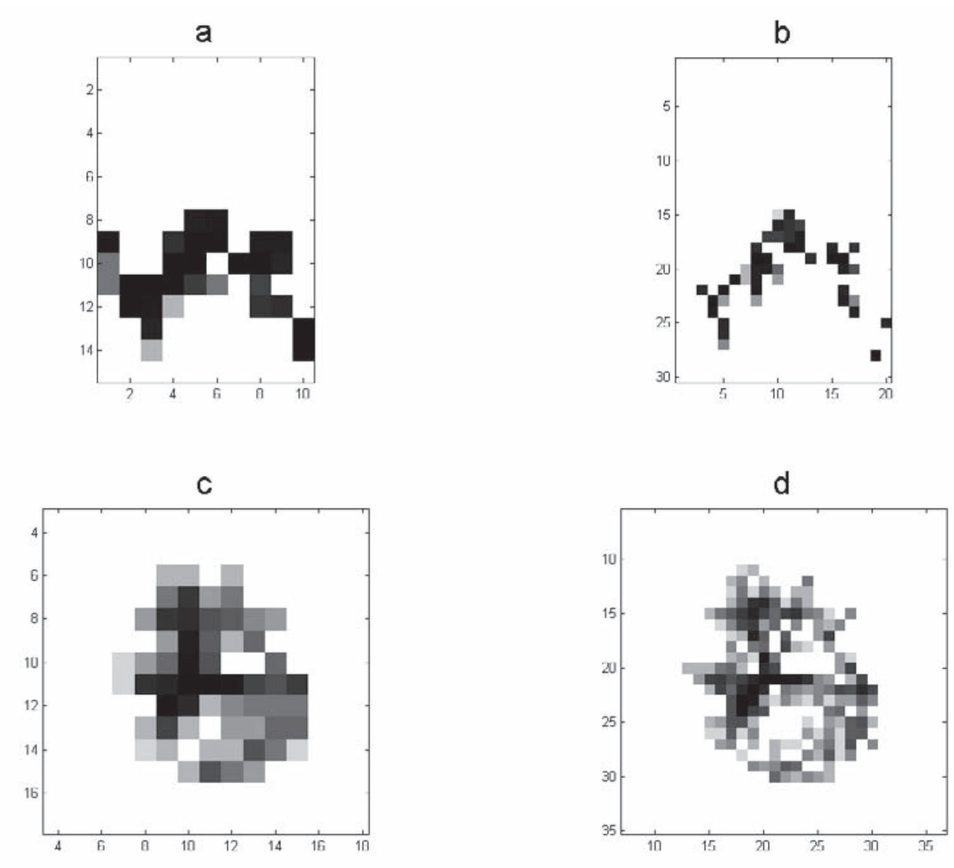


**Figure 5**—3-D cell representation of density within the crown of a small tree, for two resolutions (columns, left 10 cm cells, right, 5 cm cells) and two perspectives (rows, top, side view of vertical slice through volume, bottom, overhead view of horizontal slice through volume. Light colors are low values of density within a cell and dark cells are higher values. A) 10 cm cells, side view, vertical slice; B) 5 cm cells, side view, vertical slice; C) 10 cm cells, overhead view, horizontal slice; D) 5 cm cells, overhead view, horizontal slice.

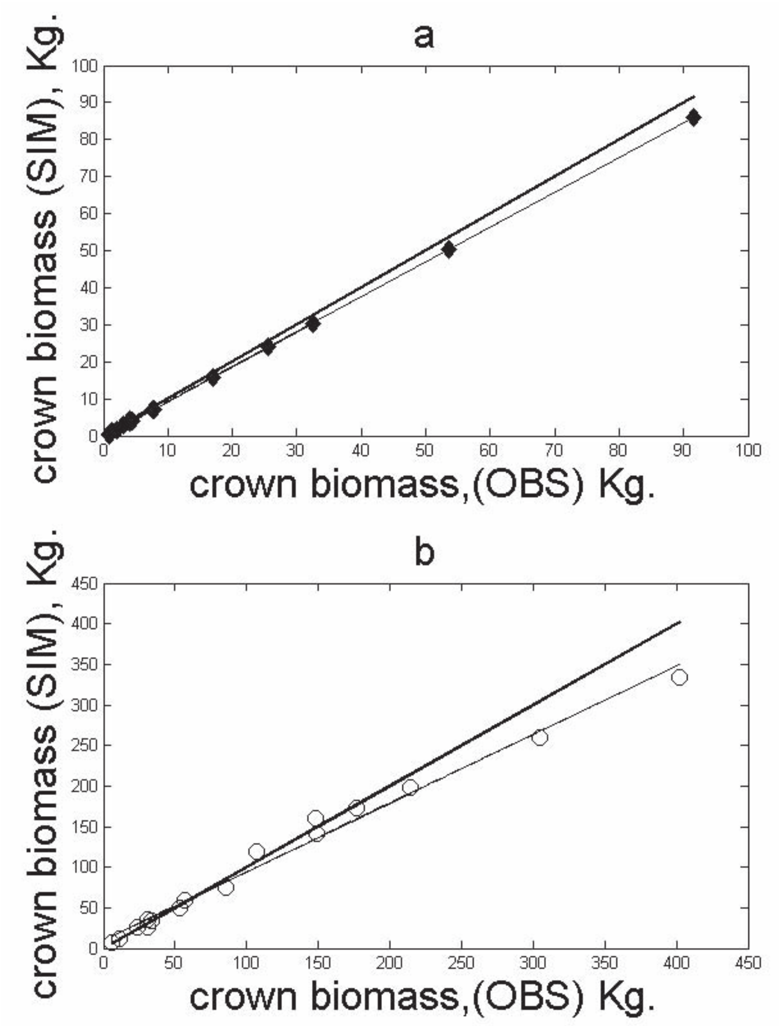


**Figure 6**—Comparison of measured total crown biomass (X axis) against crown biomass simulated with FUEL3-D (Y axis) for 16 trees used as independent "holdout" validation data from the Flagstaff site (a), and from the Ninemile site (b). Neither set of trees was used to construct modeled relationships. Solid lines in both figures represent the 1:1 line, while thinner lines are fit to the data. Correlations for fitted lines were 0.94 (a) and 0.98 (b), but slopes less than 1.0 show that modeled relationships underpredict biomass for larger trees in both sites.

**Simulating Fire and Fuel Interactions**—I demonstrate how detailed representations of fuel structure may provide insights to fire and fuel interactions with two related simulations using the physics-based fire model WFDS (Mell et al. 2005). The data used as inputs were similar to outputs from FUEL3-D, with values associated with individual 3-D cells, but were somewhat simplified as explicit connections between FUEL3-D and WFDS are still in development. The simulations were set up within a very small area similar to a wind tunnel in dimensions (8m long x 4 m wide x 4 m wide). For fire computations this area was divided into 64 x 32 x 32 cells, 0.125 m on a side. Within this small spatial domain I simulated a surface fuel bed 0.25 m in depth, 2 m wide and 6 m long, with fuel properties of excelsior (shredded aspen) and a constant moisture content of 6.3%. Three simulated trees were placed with the center of their stems at 2 m, 4.5 m and 6 m along the centerline of this fuel bed (Figure 7). WFDS represents trees and other

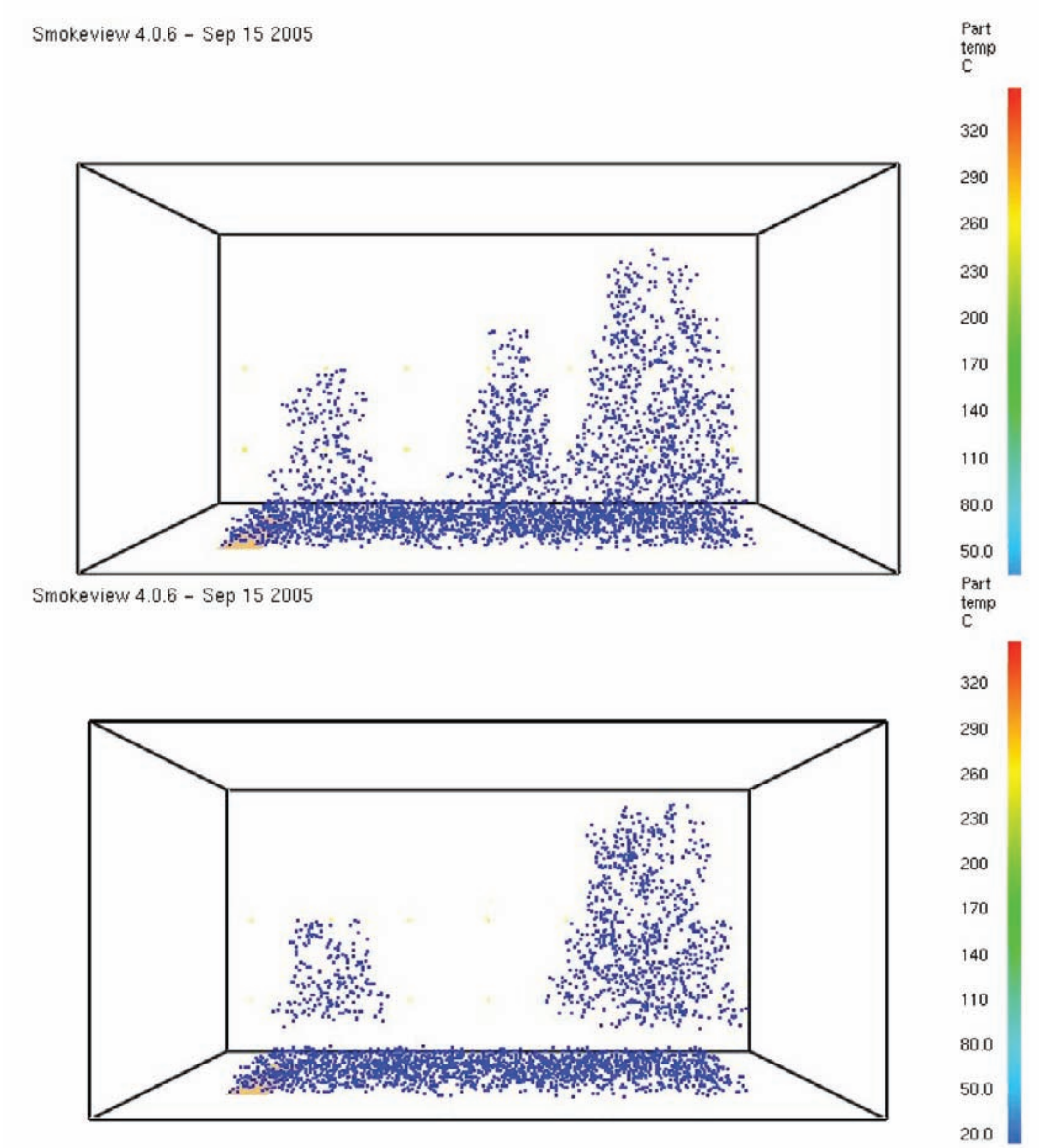


**Figure 7**—Comparison of two simulations with a numerical fire model, WFDS, and highly resolved at t = 0. Top figure shows "untreated" simulation with three small trees and a surface fuel bed in a wind tunnel. The outer trees are live, with high moistures and the middle tree is dead with low moisture, representing a recently bug-killed tree. Bottom figure shows the "treated" simulation in which the middle dead tree has been removed and lower branches have been pruned to 0.75 m.

elevated fuels as collections of thermally thin particles. Each tree was defined individually with a height, height to crown base, crown radius, and available fuel moisture content. To represent gaps within the crown, the crown for each tree was defined as frustum of a right circular cone. Within the volume of that cone, each cell was either assigned fuels or was empty depending on a random number. The first and third trees were parameterized as with more gaps, to represent more gappy, live trees while the middle tree was parameterized as less gappy and dead, with a much lower moisture content. An ignitor panel was simulated at the left edge of the fuel bed to start the fire. Winds were initialized at zero but were accelerated to a constant 1.5 m/s (3.4 mph) three seconds into the simulations. The first simulation used these fuels with no modifications and represents the "untreated" case. The second simulation represents an extremely simple fuel treatment, consisting of thinning (removal of the dead, middle tree) and branch pruning (removal of fuels in the two remaining trees below 0.75 m). Both simulations were run for a duration of 120 seconds. Graphical outputs from Smokeview, the companion software to WFDS used to visualize WFDS outputs for the two simulations for t = 0, 48, 60 and 72 seconds are shown in Figures 7-10. In these figures, the small particles represent the fuels, the lighter cloud-like structures represent flames (as isosurfaces of heat release rate per unit area, in $KJ/m^2$) and the darker cloud like structures represent soot density. These simulations were not intended to provide definitive scientific results, as the spatial domains are probably too small to eliminate artifacts arising from the proximity of the boundaries, but simply to illustrate potential applications of numerical fire behavior models in fuel treatment assessments.

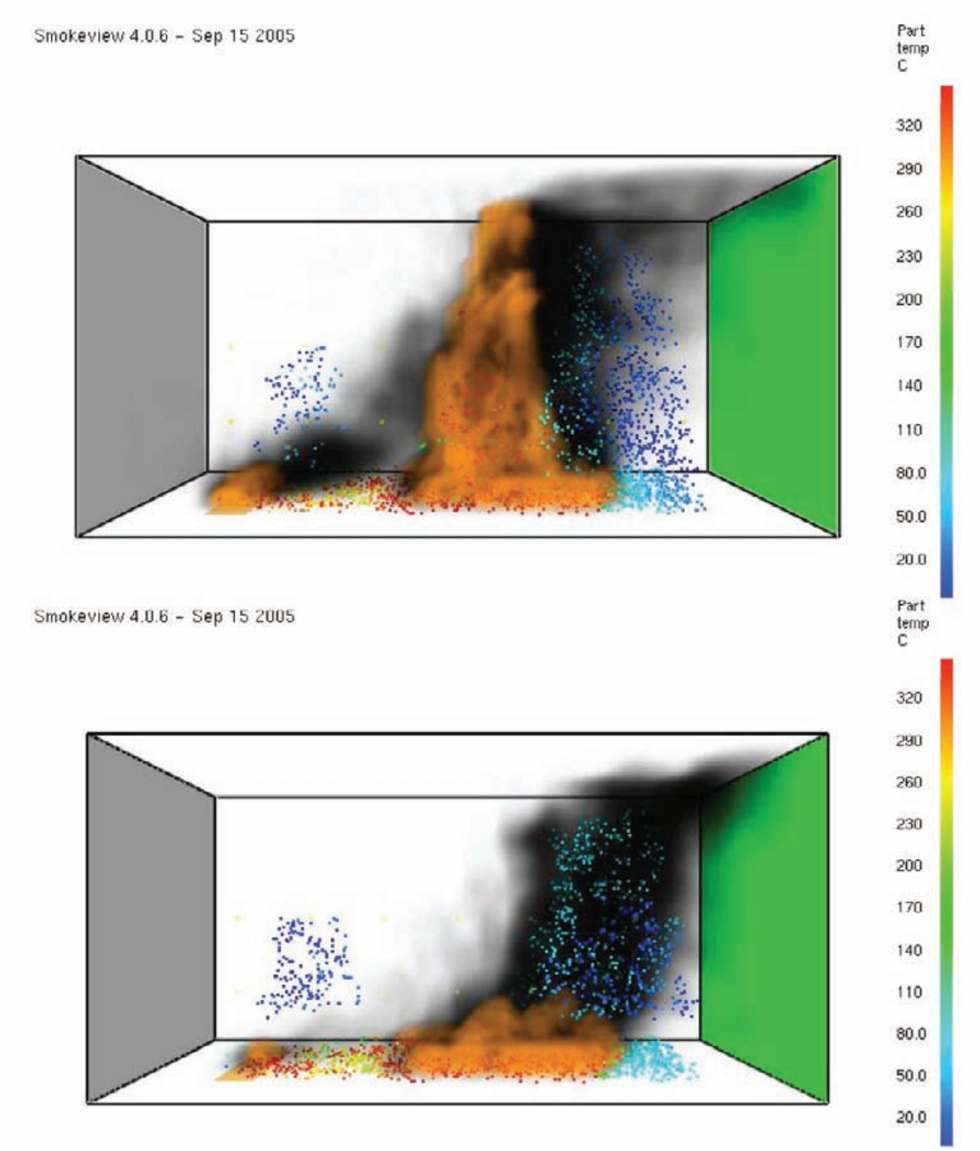


**Figure 8**—Demonstration of a numerical fire simulation with the Wildland Urban Interface Fire Dynamics Simulator (WFDS), and highly resolved fuels at t = 48 seconds. Surface fuels are burning in both simulations but the middle dead tree in the untreated simulation (top) is burning intensely.

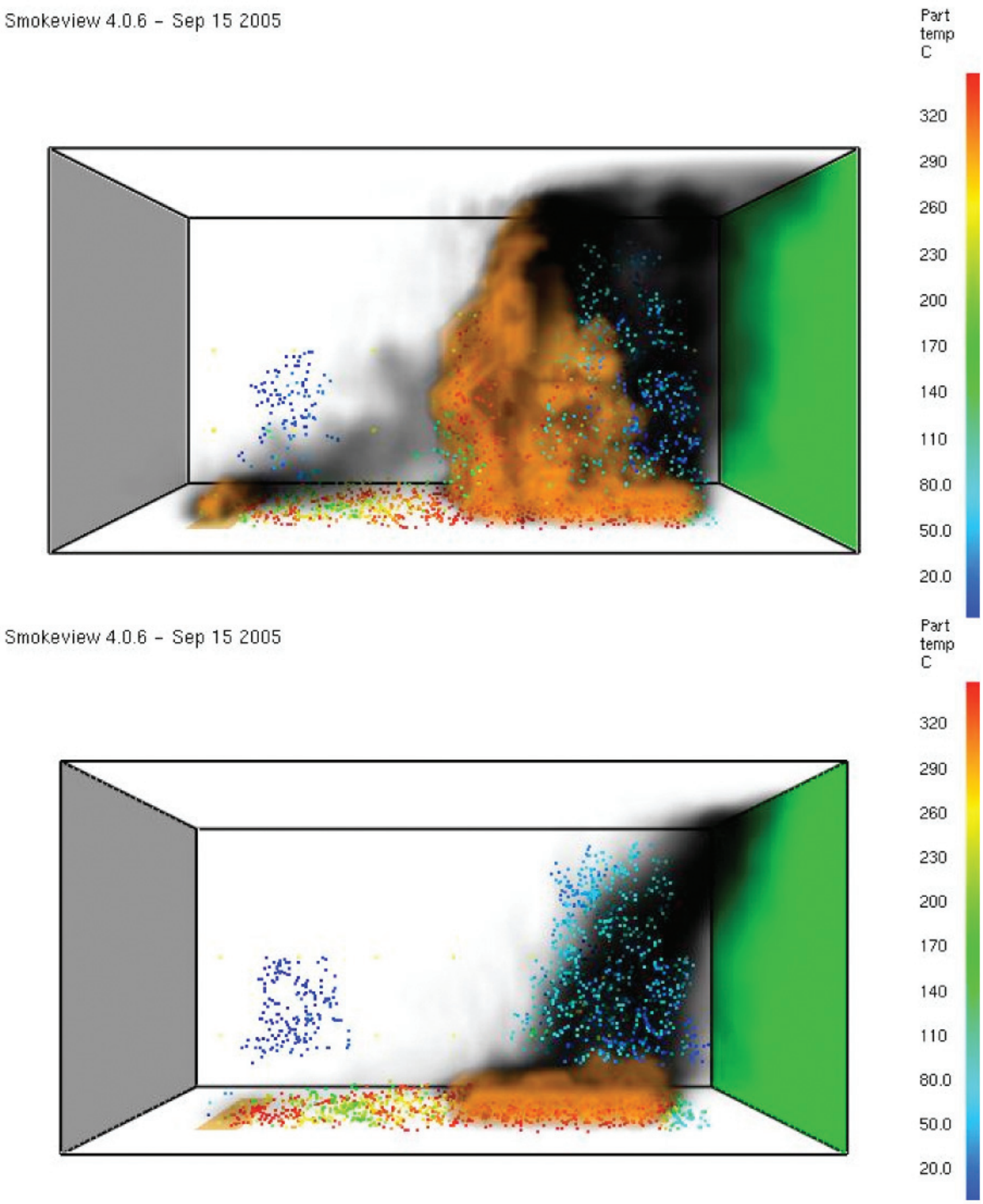


**Figure 9**—Demonstration of a numerical fire simulation with the Wildland Urban Interface Fire Dynamics Simulator (WFDS), and highly resolved fuels at t = 60 seconds. Surface fuels are burning in both simulations. Heat from the the middle dead tree in the untreated simulation (top), as well as from the surface fuels, has caused the tree at right to ignite. In the "treated" simulation (bottom) the tree at right is scorched from below but does not ignite.

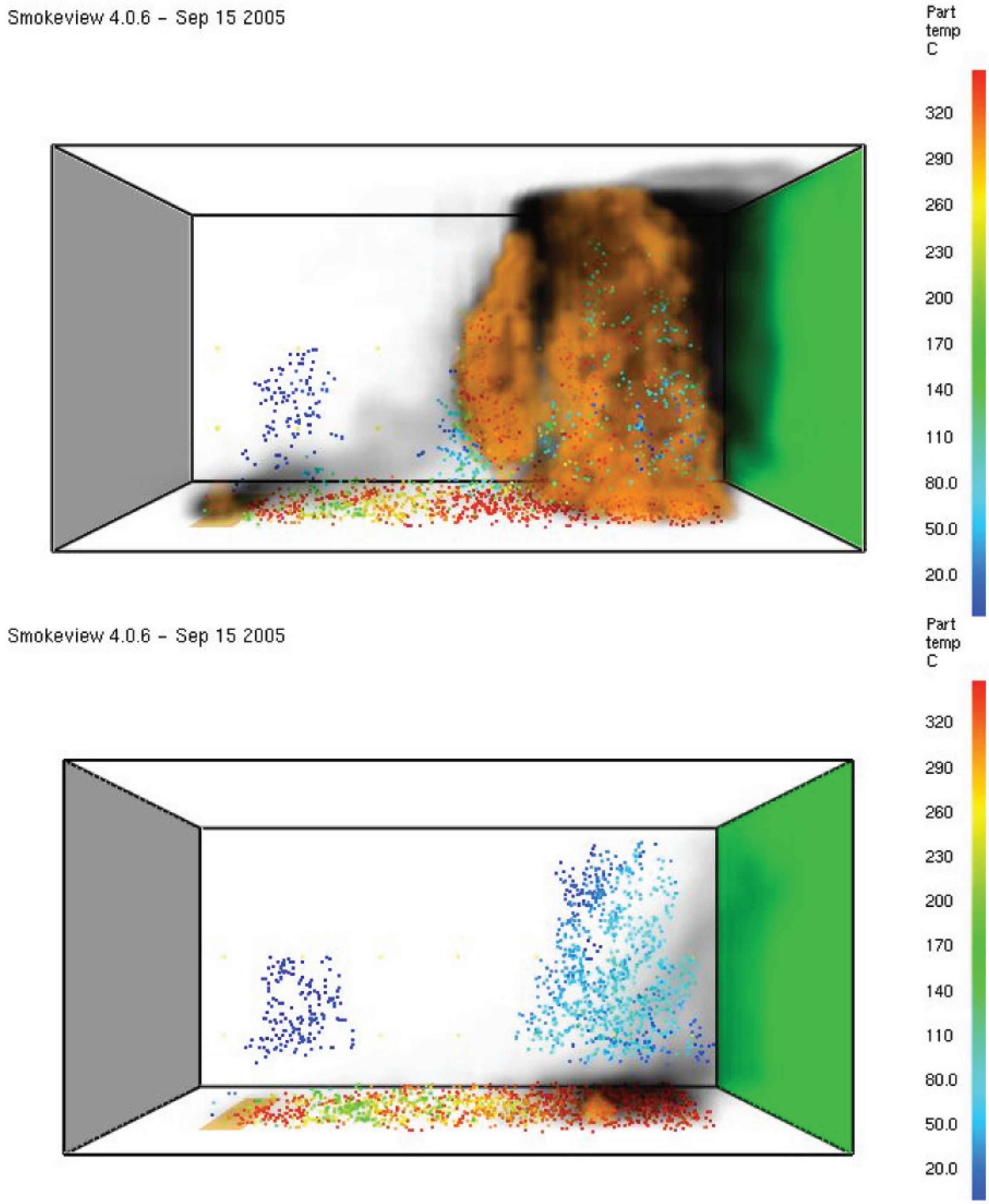


**Figure 10**—Demonstration of a numerical fire simulation with the Wildland Urban Interface Fire Dynamics Simulator (WFDS), and highly resolved fuels at t = 72 seconds. Surface fuels are burning in both simulations. Heat from the the middle dead tree in the untreated simulation (top), as well as from the surface fuels, has caused the tree at right to ignite, and it continues to burn intensely. In the "treated" simulation (bottom) the tree at right is scorched from below but does not ignite.

**Simulating Canopy Shading**—To demonstrate the application of fine scale spatial representation in assessing impacts to the microclimate I used ray tracing procedures (North 1996, Govaerts and Verstraete 1998, Brunner 1998) to simulate the shadows cast by a single tree modeled with FUEL3-D. The tree was parameterized with data from the Flagstaff field site but arbitrarily located in Missoula, Montana, at a point in space (Latitude 46.5 North, Longitude 114.0 degrees West, Missoula, Montana) and at two points in time 30 minutes apart (June 21, 2005, 14:20 and 14:50 local time) (Figures 11 and 12). Ray tracing is a spatially explicit approach for light modeling which samples beams of light between the light source (the sun) and a given object and thus is capable of representing shadows and other behaviors related to light with great detail, both in space and in time.

**Figure 11**—Visualization of a medium sized ponderosa pine tree modeled with FUEL3-D. The shadow of the tree, modeled with ray-tracing procedures, is shown at left.

**Figure 12**—Visualization of the same tree as in Figure 11 but 30 minutes later. The shadow of the tree, modeled with ray-tracing procedures, is shown at left, has moved slightly as the position of the sun changed.

# Results

## *Field Data Analysis*

Several relationships were identified from analysis of the field data (Table 1). Two sets of relationships are described: allometric relationships which relate easily measured quantities on a tree, such as DBH, to properties within the tree, such as the size class distribution of branches, and geometric relationships which describes properties and proportions. The size class distribution of individual branches on a tree, as a function of tree DBH, was positively skewed and fit well with the Weibull distribution as measured with the K-S statistic (Figure 2, Table 1). Branch biomass quantities were strongly related to branch basal diameter with power law relationships. These relationships provide the basis for the simulation of canopy structure of ponderosa pine trees.

### *Comparison/Validation*

Biomass quantities simulated with FUEL3-D compared reasonably well with both validation data sets, with correlation coefficients of 0.94 for the independent holdout data for Flagstaff site and 0.98 for the Ninemile site data (Figure 6). Slopes of linear trend lines fit to the validation data were somewhat less than 1.0 (0.95 for Flagstaff and 0.86 for Ninemile), indicating that biomass quantities for larger trees might be underestimated. The Ninemile data consisted of generally larger trees, and a very different biophysical setting, so it is difficult to determine whether the underestimation observed for larger trees is purely a function of tree size or if it has some interaction with differences between sites.

### *Numerical Fire Simulations*

The two simulations illustrate how spatial relationships within the fuel bed can result in differences in fire behavior. The two simulations had identical environmental conditions (wind speeds and fuel moistures) but removal of the center dead tree and elimination of lower branches on the remaining trees (Figure 7) resulted in differences in fire behavior between the two simulations. Figures 7-10 show the progression of the two simulations at t = 0, 48, 60 and 72 seconds, respectively. At t = 48 (Figure 8) the center tree in the untreated simulation (top) is engulfed in flame while in the treated simulation, the fire is confined to the surface fuels. At t = 60 (Figure 9), flames are moving into the crown of the large tree at right in the untreated simulation (top); at t = 72 that tree is actively flaming throughout the crown (Figure 10). At these points in time in the treated simulation the fire is burning underneath the crown of the rightmost tree but does not ascend into the crown.

**Simulating Crown Shading**—Visualizations at two points in time 30 minutes apart (Figures 11 and 12) show the detail with which individual trees and their shadows can be modeled. In full sun conditions, shadows from trees significantly reduce the direct solar radiation received at a shaded point on the ground. Direct solar radiation is a key driver of dead fine fuel moisture, raising the fuel temperature, heating the boundary layer and accelerating evaporation (Nelson 2002). Modeling shadows from individual trees may thus be applied to assess spatial variability in surface fuel moistures and changes in such patterns arising from fuel treatments.

## Discussion

The models which form the basis of our current operational capacity to assess fuel treatments, namely, the fire behavior model BEHAVE (Rothermel 1972) and the stand growth model PROGNOSIS (Stage 1973), were developed at a time when many processes in combustion science and plant growth were poorly understood, and when both computational resources, and the data which could be used as inputs to predictive models were limited. Advances in computing resources, information technology and geospatial applications such as GPS, GIS and remote sensing change the nature of what is possible in assessing fuel treatments. New sensors such as LIDAR make it possible to measure individual tree stems and branch heights (Henning and Radtke 2006), individual crown diameters (Popescu et al. 2003) and estimate other stand characteristics (Nelson et al. 1988). The continuing development of such technologies suggests that detailed modeling of fire and fuels will only become more accessible to the wildland fire community as time goes on.

The FUEL3-D model is still in development and should be viewed as a work in progress. The same holds true, to a lesser degree, for the numerical fire models themselves which represent a rapidly advancing but still emerging field in fire science. Continuing development of the FUEL3-D model will provide avenues by which important knowledge gaps regarding wildland fuel properties, microclimate-fuel dynamics, fire-fuel interactions and fire effects can be addressed. Although the model is currently more appropriate for research use, a management appropriate configuration will be developed as soon as the underlying structure of the model is sufficiently mature.

The ability to represent the spatial structure of vegetation in detail across a range of scales will facilitate improvements in our understanding of fundamental fuels science. Fuel beds can be constructed describing any configuration of trees and shrubs of any size. By building fuel beds from individual trees and shrubs (and associated surface fuels), loss of relevant detail and scale-dependencies associated with fuel classifications is avoided (Sandberg et al. 2001). At present there is no way that fundamental wildland fuel properties, such as surface area to volume ratio, the size distribution of particles or distribution of mass within a tree crown, can be easily calculated. With FUEL3-D these quantities can be calculated from the simulated structure, tested and calibrated. The flexibility with which FUEL3-D can represent the architecture of trees and shrubs makes it possible to develop species-specific fuel models. Differences in crown architecture between species likely play key roles in how fire burns through a stand and how that stand responds to fuel treatment over time. This provides stronger linkages between silviculture, ecosystem function and fuel management such that fuel treatments can be considered not only in terms of their potential impacts on fire behavior but also on other ecosystem components.

Detailed modeling of wildland fuels in space improves in our ability to assess changes in microclimate arising from fuel treatments, as well as to better understand the complexities of natural stands. A large number of spatially explicit light models have been developed (see Brunner 1998) but the majority of these focus on plant growth and thus do not consider fluctuations in solar radiation at temporal scales finer than a few weeks, as this tends to be the limit at which plant growth can be modeled (Brunner 1998). In fire and fuels applications such time scales are likely too coarse to capture much of the important dynamics, particularly with respect to dead fine fuel moisture, which exhibit significant sensitivity to solar radiation over short time periods (Nelson 2002). Current FUEL3-D research inquiries in this arena are directed at linking a ray tracing procedure to a dynamic fuel moisture model (Nelson 2002) in space. This will enable spatially and temporally explicit modeling of surface fuel moisture dynamics which can be used to quantitatively compare fuel treatments. Such detailed modeling will also likely also be of use in modeling shrub and grass growth response over time, a factor important to the effective duration of fuel treatments.

By quantitatively describing fuels at higher detail, FUEL3-D will promote an improved understanding of fire and fuels interactions. In conjunction with numerical fire behavior models such as FIRETEC or WFDS it will be possible to more precisely study transitions from surface to crown fire and develop species-specific thinning spacing guidelines. Analyses across scales will help to systematically identify conditions when greater complexity in modeling is required, and simpler conditions in which it is not. Correlative relationships observed through more intense numerical studies may be used to refine existing operational models. One advantage of FUEL3-D is its independence from any specific fire behavior model and its assumptions and limitations. At present the model is being designed to work with two numerical fire models, FIRETEC (Linn et al. 2002) and WFDS (Mell et al. 2005). As other models appear or as these models change FUEL3-D will be able to provide the needed inputs. The independence of the fuel model from particular fire behavior models provides flexibility and facilitates comparisons between models.

Finally, modeling fuel-fire interactions at fine scales will aid in a tighter coupling between fire behavior and fire effects. Most fire effects calculations are carried out as point calculations, where fuel consumption at a point or mortality of an individual tree are considered (Reinhardt et al. 2001). At present it is difficult to rectify the homogeneous stand-based fire behavior calculations from operational fire behavior models with point level fire effects predictions. Incorporation of finer detail in representation of fuels with FUEL3-D, and detailed spatially explicit fire behavior models will provide a basis for linkages between fire behavior, fuels and fire effects than has been possible before. This will improve our ability to define burn window prescriptions and anticipate the consequences of treatments or wildfire.

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## Literature Cited

Andrews, P. L., C. D. Bevins, and R. C. Seli. BehavePlus fire modeling system–version 2.0: User's Guide. USDA Forest Service, Rocky Mountain Research Stations, General Technical Report-RMRS-GTR-106WWW.

Berezovskava, F .S., Karev, G. P., Kisliuk, O. S., Khlebopros, R. G., and Y. L. Tsel'niker. 1997. A fractal approach to computer-analytical modeling of tree crowns. Trees 11:323-327.

Bradstock, R. A., and A. M. Gill. 1993. Fire in semi-arid, Mallee shrublands: size of flames from discrete fuel arrays and their role in the spread of fire. Int. J. Wildland Fire 3(1):3-12.

Brandle, J. R., B. B. Johnson, and D. D. Dearmont.1984. Windbreak economics: the case of winter wheat production in eastern Nebraska. Journal of Soil and Water Conservation 39(5):339-343.

Brunner, A. 1998. A light model for spatially explicit forest stand models. Forest Ecology and Management 107:19-46.

Burrows, N. D. 2001. Flame residence times and rates of weight loss of eucalypt forest fuel particles. Int. J. Wildland Fire 10:137-143.

Busing, R. T. and Mailly, D. 2004. Advances in spatial, individual-based modeling of forest dynamics. Journal of Vegetation Science 15:831-842.

Canham, C. D., K. D. Coates, P. Bartemucci, and S. Quaglia. 1999. Measurement and modeling of spatially explicit variation in light transmission through interior cedar-hemlock forests of British Columbia. Can. J. For. Res. 29:1775-1783.

Enquist, B. J. 2002. Universal scaling in tree and vascular plant allometry: toward a general quantitative theory linking plant form and function from cells to ecosystems. Tree Physiology 22:1045-1064.

Finney, M. A. 1998. FARSITE: Fire Area Simulator — Model development and evaluation. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-4.

Fons, W. L. 1946. Analysis of fire spread in light forest fuels. Journal of Agricultural Research 72(3):93-121.

Fosberg, Michael A.; Deeming, John E. 1971. Derivation of the 1- and 10- hour timelag fuel moisture calculations for fire-danger rating. Research Note RM-207. Fort Collins, CO: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station. 8 p.

Godin, C. 2000. Representing and encoding plant architecture: a review. Ann. For. Sci. 57:413-438.

Godin, C., O. Puech, F. Boudon, and H. Sinoquet. 2004.Space occupation by tree crowns obeys fractal laws:evidence from 3D digitized plants. 4th International Workshop on Functional-Structural Plant Models, 7-11 June 2004, Montpellier, France. Edited by C. Godin et al: 79-83.

Govaerts, Y. M. and Verstaete, M. M. 1998. Raytran: a Monte Carlo ray-tracing model to compute light scattering in three dimensional media. IEEE Transactions on Geoscience and Remote Sensing, 36: 493-505.

Grissino-Mayer, H. D. 1999. Modeling fire interval data from the American Southwest with the Weibull distribution. International Journal of Wildland Fire. Vol. 9, no. 1 Mar. 1999: 37-50.

Helvey, J. D., and J. H. Patric. 1965. Canopy and litter interception by hardwoods of eastern United States. Water Resources Research 1:193-206.

Henning, J. G., and P. J. Radtke. 2006. Detailed stem measurements of standing trees from ground-based scanning LIDAR. Forest Science 52(1):67-80.

Jensen, A. M. 1983. Shelterbelt Effects in Tropical and Temperate Zones. Report IDRC-MR80e. Agriculture, Food and Nutrition Sciences Program, International Development Research Centre. Ottowa, Canada. 61 pp.

Kuuluvainen, T. and T. Pukkala. 1987. Effect of crown shape and tree distribution of shade. Agric. Forest Meterology 40:215-231.

Linn, R. R., and P. Cunningham. 2005. Numerical simulations of grass fires using a coupled atmosphere-fire model: basic fire behavior and dependence on wind speed. J. Geophysical Research 110:D18107.

Linn, R. R., Reisner, J., Colman, J. J., and J. Wintercamp. 2002. Studying wildfire behavior using FIRETEC. Int. J. Wildland Fire 11:233-246.

Mandelbrot, B. B. 1983. The fractal geometry of nature. W. H. Freeman and Company, New York, New York, USA.

Mell, W. E., J. J. Charney, M. A. Jenkins, P. Cheney and J. Gould. 2005. Numerical simulations of grassland fire behavior from the LANL-FIRETEC and NIST-WFDS models. EastFIRE conference, May 11-13, 2005. George Mason University, Fairfax, VA.

Nelson, R. R., R. Swift, and W. Krabill. 1988. Using airborne lasers to estimate forest canopy and stand characteristics. J. Forestry. 86:31-38.

Nelson, Ralph. M., Jr. 2002. Prediction of diurnal change in 10-h fuel stick moisture content. Canadian Journal of Forest Research 30:1071-1087.

Niklas, K. J. 1986. Computer simulated plane evolution. Scientific American 254:78-86.

North, P. R. J. 1996. Three-dimensional forest light interaction model using a Monte Carlo method. IEEE Transactions on Geoscience and Remote Sensing, 34:946-956.

Oke, T. R. 1978. Boundary Layer Climates. Methuen, London. 372 pp.

Ozier-Lafontaine, H. O., F. Lecompte and J. F. Sillon. 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).

Popescu, S. C., R. H. Wynne, and R. F. nelson. 2003. Measuring individual tree crown diameter with lidar and assessing its influence on estimating forest volume and biomass. Can. J. For. Res. 29:564-577.

Potter, B. E. 2002. Dynamics-based view of atmosphere-fire interactions. International Journal of Wildland Fire 11:247-255.

Pukkala, T., Kuuluvainen, T. and P. Stenberg. 1993. Below canopy distribution of photosynthetically active radiation and its relation to seeling growth in a boreal *Pinus sylvestris* stand: a simulation approach. Scand. J. Forest Research. 8:313-325.

Reifsnyder, W. E. and H. W. Lull. 1965. Radiant energy in relation to forests. USDA Forest Service. Technical Bulletin No 1344. 111 pp.

Reinhardt, E. D., R. E. Keane, et al. 2001. Modeling fire effects. International Journal of Wildland Fire 10: 373-380.

Richarson, A. D., and H. Z. Dohna. 2003. Predicting root biomass from branching patterns of Douglas-fir root systems. OIKOS 100:96-104.

Rothermel, R. C. 1991. Predicting behavior and size of crown fires in the northern Rocky Mountains. USDA For. Serv. Res. Pap. INT-438.

Rothermel, Richard C. 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 40 p.

Sandberg, D. V., Ottmar, R. D., and G. H. Cushon. 2001. Characterizing fuels in the 21st Century. Int. J. Wildland Fire 10:381-387.

Scott, J. H., and E. D. Reinhardt. 2002. Estimating canopy fuels in conifer forests. Fire Manage. Today. 62:45-50.

Shinozaki, K., Yoda, K., Hozumi, K. and T. Kira 1964.A quantitative analysis of plant form — the pipe model theory. I. Basic analysis. Jpn. Ecol. 14:97-132.

Stage, A. R. 1973. Prognosis model for stand development. USDA Forest Service, Rocky Mountain Research Stations, Research Paper INT-137. 32 pp.

VanWagtendonk, J. W. 1996. Use of a deterministic fire growth model to test fuel treatments. Sierra Nevada Ecosystem Project: Final report to Congress, Vol. II, Assessments and scientific basis for management options. Davis: University of California, Centers for Water and Wildland Resources.

Vogel, M., and F. A. Williams. 1970. Flame progagation along matchstick arrays. Combustion Science and Technology. 1:429-436.

Weber, R. O. 1990. A model for fire propagation in arrays. Math'l Comput. Modelling 13(12):95-102.