VI International Conference on Forest Fire Research
D. X. Viegas (Ed.), 2010

Crown Fuel Spatial Variability and Predictability of Fire Spread

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Abstract
Fire behavior predictions, as well as measures of uncertainty in those predictions, are essential in operational and strategic fire management decisions. While it is becoming common practice to assess uncertainty in fire behavior predictions arising from variability in weather inputs, uncertainty arising from the fire models themselves is difficult to assess. This is the case with fires in crown fuels and the operational fire behavior models used in the United States, where model assumptions, such as fuel homogeneity and steady-state spread, limit the capability of those models to provide reliable results, possibly leading to uncertainties of unknown magnitude. An emerging body of work with dynamic physics-based fire models illustrates the capabilities of those models to address potentially important factors that are not considered by operational models, such as fuel heterogeneity and transitional behaviors. In this investigation we used a dynamic, physics-based fire model, FIRETEC, to explore variability in the forward spread rate of a fire arising from spatial variability in crown fuels. We generated 25 different spatial configurations of trees with four different clumping patterns, for a total of 100 different simulated forest stands. Using FIRETEC we simulated fire through each of these stands, holding the ignition and weather inputs constant. Analyses assessed differences in spread rates between clumping groups and arising from differences in canopy cover and total fuel, as well as differences in variability in spread rate between clumping groups. Differences in spread rates between groups and due to canopy cover and total fuel were not significant, largely due to high variability within groups; differences in variance in spread rate between clumping groups was statistically significant (p-value 0.0007). Variability in spread rate increased substantially as gaps between tree clumps got larger, with > 60% difference in overall spread rate observed between the lowest rate of spread and the highest rate of spread. Results suggest a certain inherent unpredictability in fire behavior that can largely be attributed to fine scale fire-fuel-atmosphere interactions which are by their nature difficult to predict beforehand. Self-determining physical fire models do not predict, but rather observe outcomes; however, ensemble runs with physical fire models can be used to quantify variability in fire behavior arising from sources that are not considered by operational models. Our study suggests a need for a paradigm shift in fire behavior modeling which emphasizes identifying sources of variability and estimating their magnitude over pure prediction of spread rates.

Keywords: spatial heterogeneity, fire behavior, FIRETEC, rate of spread, variability

1. Introduction

Fire rate of spread (ROS) refers to the horizontal distance that a fire moves per unit of time, and is a primary output of operational fire spread models and related tools in the United States such as NEXUS(Scott and Reinhardt 2001), FVS-FFE (Reinhardt and Crookston 2003), FARSITE (Finney 2004) and BehavePlus (Andrews et al 2008). Predictions of ROS are of paramount importance in wildland fire management and form the basis for numerous operational decisions, including fire suppression tactics, designation of safety zones and contingency evacuation plans for communities; underestimation of ROS can result in fatalities (Chandler *et al.* 1983, Cheney *et al.* 2001). For this reason, it is important that ROS be predicted as accurately as possible, and that potential sources of uncertainty in ROS be identified and quantified.

Operational fire spread models in the United States have been shown to underpredict ROS, both for surface fires (Van Wagtendonk and Botti 1984) and for crown fires (Cruz and Alexander 2010). Cruz and Alexander (2010) attributed underprediction of ROS in crown fires to several different factors within the larger modeling framework common to all these models, which links Rothermel surface fire and crown fire ROS models (Rothermel 1972, Rothermel 1991) with Van Wagner's crown fire initiation and propagation models (Van Wagner 1977,Van Wagner 1993). The crown fire ROS calculated by Rothermel's crown fire spread model (Rothermel 1991) is made on the basis of a correlative relationship with Rothermel's surface fire spread model (Rothermel 1972).

The Rothermel model was developed primarily on the basis of laboratory burn experiments in homogeneous fuels and assumes that fuels are homogeneous, continuous and contiguous to the ground. These assumptions and other aspects of the Rothermel model jeopardize its applicability toward predictions of crown fire ROS (Cohen et al 2006) and also prevent quantification of variability in ROS that could arise from factors that are not addressed by this modeling framework. Fire managers relying on these predictions are thus forced to make decisions on the basis of information that may be both biased and subject to uncertainty of unknown magnitude.

As weather and topography are largely outside our control, the primary means by which fire managers could modify ROS or other aspects of fire behavior is through manipulation of the fuel bed. This is the underlying logic behind fuel treatments such as thinning. Variability within the fuel bed, either natural or anthropogenic, thus represents an important potential source of variability in ROS. Several studies have demonstrated the impact of fuel particle size, shape, composition and arrangement (Burrows 2001) and, particularly, distance between fuel particles (Fons 1946, Vogel and Williams 1970, Weber 1990, Bradstock and Gill 1993) on fire spread and behavior. It follows, then, that variability in these characteristics could result in variability in ROS.

In recent years, dynamic physics-based numerical fire behavior models have been developed which can provide insights regarding fundamental aspects of fire propagation (Linn 1997, Morvan and Dupuy 2001, Dupuy and Morvan 2005, Mell et al 2007) and which are capable of addressing spatial fuel heterogeneity at the scale of individual trees (Linn et al. 2005, Mell et al. 2009). These models simulate the coupled interactions between the fire and fuels (such as canopy drag effects on convective flows) and the fire and the atmosphere (such as changes in wind direction and velocity arising from heat-induced buoyancy). Unlike operational models which are semi-empirical in nature, these models have self-determining spread rates; variability in spread rates is an emergent property of such models. Such models are thus ideally equipped to study the effects of spatial fuel variability on variability in ROS.

2. Objectives

Our objective was to use a three dimensional numerical fire model, HIGRAD-FIRETEC, to investigate and understand the effect of spatial variability in crown fuels on the forward spread rate of a fire. We generated 25 different spatial configurations of the same set of trees with four different clumping patterns (no clumping, small, medium and large clumps), for a total of 100 different simulated forest stands. Using FIRETEC we simulated fire through each of these stands, holding the ignition and weather inputs constant. Analyses assessed effects of clumping group, total fuel and canopy cover on ROS and differences in variability in ROS between clumping groups.

3. Methods

Model description

HIGRAD/FIRETEC is a coupled atmospheric dynamics/wildfire model based on conservation of mass, momentum, energy, and chemical species (Linn 1997). Coupling arises from a buoyancy term in the fully compressible, three dimensional Navier-Stokes equations comprising the governing equation set of the atmospheric dynamics component (HIGRAD)(Reisner et al. 2000[a], Reisner et al. 2000b). Atmospheric conditions couple with the fire/fuels component (FIRETEC), primarily through drag forces acting on fuels, convective heat exchange, and advection/turbulent mixing of oxygen. HIGRAD/FIRETEC has been used to model wildfire behavior over an extensive set of atmospheric and environmental conditions including rugged terrain, variable winds, and landscape scale heterogeneous fuels (Cunningham and Linn 2007, Linn et al. 2002, Linn et al. 2007, Linn et al. 2005, Linn and Cunningham 2005, Pimont et al. 2009). As the formulation of the model has been presented in previous work we focus here on the numerical experiment carried out for this study.

Numerical experiment: domain and boundary conditions

To test the effect of spatial variability in crown fuels on spread rates, we used the same simulation layout, a rectangular domain 320 m in length, 160 m in width and 615 m in height (Figure 1), for all simulations. Horizontal resolution was 2 meters; vertical resolution stretched, increasing with height, using a sigma cubic polynomial. A pre-developed ambient wind field which realistically incorporated effects of the forest canopy on wind flow, generated by running HIGRAD/FIRETEC with the base case forest (described below) and without a fire, entered the domain at one end, shown at the bottom of Figure 1. This wind field had a maximum forward wind speed (zonal velocity component, u) of 6 m s^{-1} above the forest canopy or 21.6 km hr^{-1}; wind speed near and below the canopy was reduced significantly by canopy drag effects. As the forest canopy extended to around 18m, winds at 10m were strongly influenced by drag effects, but a representative U_{10} open wind speed would be about 4 – 6 m s^{-1} (14.4 – 21.6 km hr^{-1}) for these simulations. Meridional and vertical velocity components at each boundary are set to a 0 m s^{-1} constant vertical profile. A 10 m strip along each domain edge was used as a ‘relaxation’ boundary zone, where flow velocities were incrementally (with distance) modified to ‘relax’, or conform to the vertical profile developed by the pre-developed wind field. This process is implemented to provide minimally reflecting, non-cyclic boundary conditions**.**

Each simulation ran for 370 s of simulation time, with a time step of 0.01. All inflow and outflow boundary conditions, initial conditions, and ignition pattern were identical for all simulations. The ignition pattern consisted of an ignition strip, measuring 40 meters in Y, from y = -20 to y= 20, and 2m in x at x = -80, within which temperatures ramped up from ambient temperature (300 K) up to 1000 degrees K at a rate of 350 K s^{-1}. Ignition began at t=10s such that initial hydrodynamic conditions were not influenced by heat.

Fuels representation

Surface fuels consisted of a homogeneous grass layer with a fuel bed depth of 0.5 m, a fuel load of 0.45 kg m^{-2}, and a surface area to volume ratio of 4000 $m^{-1,}$ similar to Anderson's fuel model 3 (tall grass) (Anderson 1982) but with a slightly lower fuel load and fuel bed depth. Surface fuel moistures were set at ten percent of dry weight.

To represent crown fuel, a base case forest was established consisting of 2000 individual trees, randomly located within the 5.12 ha (320 m x 160 m) spatial domain, producing a stand density of roughly 391 stems per ha. Each tree had an identical crown, 12 m in length and 5 meters in diameter, but these crowns were translated up and down with offsets sampled from a normal distribution (with μ =4.5 m, σ= 0.75) to produce variability in the vertical distribution of crown fuel. Using the method described in Linn et al 2005, trees were modeled as parametric volumes, consisting of an upper and lower paraboloid, within which fuel is concentrated toward the outside edges of the volume. As adjacent trees can each contribute fuel to the same cells, a maximum fuel density for any given cell, ρ_{max} , was set to a value of 0.48 kg m^{-3} (Linn et al. 2005) to ensure that fuel quantities remained within reasonable limits. This per cell limit refers to the maximum fuel density within a tree crown, not the macroscopic "whole stand" canopy bulk density used in operational fire behavior models, which is considerably lower because it incorporates voids between trees.

The base case forest was then divided into three parts. Within the first area (with respect to where the fire and wind are coming from), extending from -160 to -40 m, forest fuels were held constant for all simulations. This was followed by an area in which fuels were modified, called the Fuel Modification Zone (FMZ), which extended from x=-40 to x = 80, and from y = -80 to y = 80, shown as a shaded area in Figure 1, followed by another area after the FMZ in which forest fuels were held constant. The purpose of the initial area was to minimize differences between simulations in the conditions under which the fire developed prior to entering the FMZ. The area extending from x=80m to x = 140m was designated as the far end pre-boundary zone. This zone of unmodified fuel ensured that effects of coupled hydrodynamics and vegetation induced drag were consistent in all simulations near the outflow boundary of the domain.

Base case trees whose coordinates fell within the FMZ were rearranged into 25 replications each of four different spatial configuration scenarios were rearranged into different four different clumping scenarios: random, small, medium and large, according to a Neyman-Scott process (Neyman and Scott 1958) (**Table 1**). These clumping groups represent a spectrum of increasing clump size as well as distance between clumps. In the Neyman-Scott process, a number of centroid points is drawn from a Poisson distribution; trees are then randomly assigned to one of these centroids and their coordinates were translated to a new position randomly determined within the specified radius of that centroid. In each case the same set of simulated tree crowns was rearranged into clumps randomly. This process produces clumped distributions of points. As in the case of the base case forest, a maximum cell density of 0.48 kg m^{-3} was imposed to prevent excessive fuel quantities. This resulted in a reduction in both the total amount of fuel and in percent canopy cover between clump groups. As both the total amount of fuel and percent canopy cover are influential variables in operational fire models, this provided us with a means of statistically testing the relative influence of total fuel quantity, percent canopy cover and differences in spatial configuration on ROS.

The simulations were performed on the high performance computing facilities at Los Alamos National Laboratory, using 64 processors per ensemble member for a run time of approximately 12 hours. The entire 100 member ensemble of simulations was completed in less than 48 hours.

Statistical analysis of forward spread rates

For each simulation, we calculated the rate of spread for the fire to cross the fuel modification zone. The fuel modification zone measures 120 meters wide. Because the horizontal resolution is 2 m, this calculation was done as the distance between the midpoints of the cells at the boundaries of the fuel modification zone (-39 and 79, in x, respectively), divided by the time that the fire arrived at those coordinates. The exact time of arrival was determined (to the nearest 0.01 s) from fuel consumption of the surface fuels.

To assess differences in ROS between clumping groups and to determine whether ROS could be predicted from total fuel or canopy cover , we fit the data with a generalized linear mixed effects model (McCullagh and Nelder 1989). We evaluated the goodness of fit with Akaike's Information Criterion (AIC) (Akaike 1974), a relative measure of fit used to make comparisons between a set of statistical models attempting to describe the same phenomena. The model with the lowest score is considered the best fit.

We tested for significant differences in variance in spread rate between clumping groups using the rank-based Kruskal-Wallis- modified, robust Brown-Forsythe, Levene-type test based on the MAD (Brown and Forsythe 1974, Kruskal and Wallis 1952, Levene 1960).

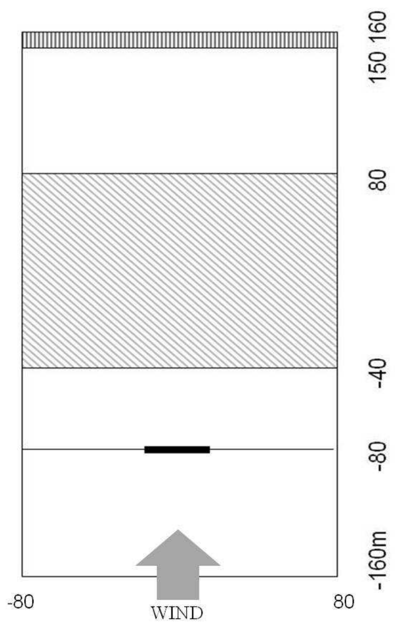

Figure 1: Simulation Layout. The spatial domain measured 320 m x 160 m x 615 m (vertical). The shaded area represents the Fuel Modification Zone (FMZ) within which the same set of trees were randomly clumped into different clumping patterns. The dark thick line in the lower middle of the figure represents the ignition start location.

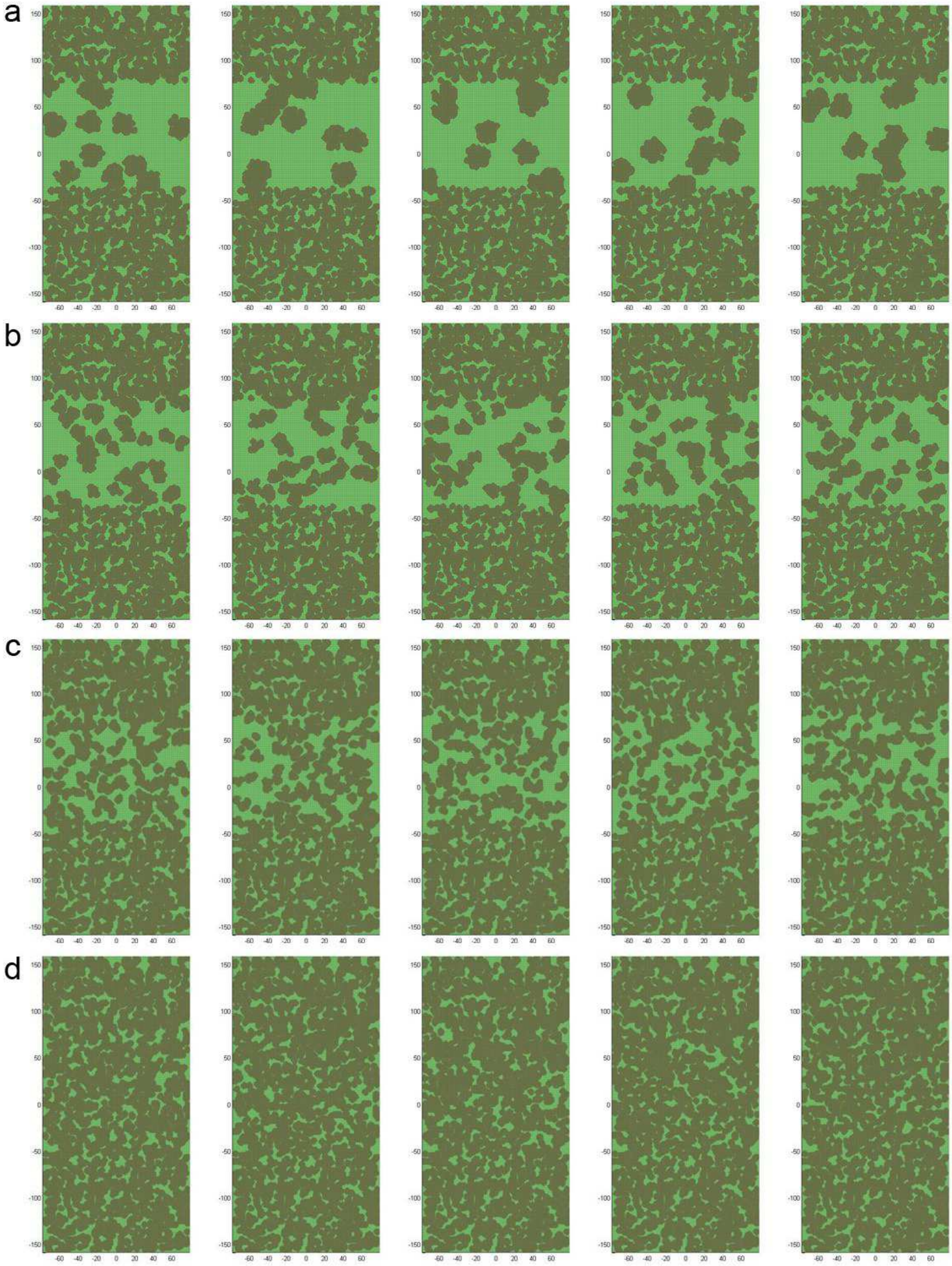

Figure 2: Example spatial configurations. For each of the four clump groups, Large (a), Medium (b), Small (c), and no clumping (d), five example spatial configurations are presented; 25 different replicates were generated for each group. The same 2000 trees were used in simulations. Trees within the Fuel Modification Zone were rearranged into clumps of different sizes.

4. Results

Twenty-five replicate spatial configurations were produced for each of the four clumping groups. Representative examples of each clumping group are presented in **Figure 2**. Our approach for generating fuel cases resulted in a range in the total amount of fuel, as well as canopy cover, across simulations; differences within a clumping group were small relative to differences between groups. Total fuel and canopy cover both decreased as the spatial scale of clumping increased, with the average total fuel in the largest clump group being about 60% less than in the smallest clump group (**Table 1**); variability in total fuel and canopy cover, increased with spatial scale of clumping (**Table 1**).

Across all groups, average fire spread rates across the Fuel Modification Zone were 0.578 m s^{-1}, or 34.6 m min^{-1}. With surface fuel moisture content of 10% and U_{10} open wind speeds of 4 – 6 m s^{-1} (14.4 – 21.6 km hr^{-1}) , these spread rates are comparable to crown fire spread rates in several forest types reported by Cruz and Alexander (2010), but it is difficult to make direct comparisons between these simulations and rates of spread observed for real fires as fuel and environmental conditions, such as winds, in those fires are not precisely known.

Rates of spread for the fire to cross the fuel modification zone varied widely; variability in ROS increased as gaps between canopy clumps got larger (**Table 2**, **Figure 3**). Differences in variance between groups were statistically significant, with the Brown-Forsythe, Levene-type test statistic of 6.1682 and corresponding p-value of 0.0007.

Statistical analysis with the generalized linear mixed effects model found no significant differences in spread rates between clump groups (Kruskal and Wallis 1952),(p-value 0.229). This lack of significant differences between clump groups is clearly related to the high within group variability (Figure 3). Canopy cover and total fuel were highly correlated (Pearson's r = 0.98) so very little additional information was provided if both variables were used; inclusion of canopy cover or total crown fuel did not improve prediction of rate of spread, with a higher (and thus poorer) AIC score after inclusion of those variables (AIC -213.9 with canopy cover, AIC -229.7 without canopy cover). Rates of spread ranged, across all simulations, from 0.46 m s^{-1} (1.65 Km hr^{-1}) to 0.77 m s-1 (2.77 Km hr^{-1}) (**Table 2**). This difference in ROS, of .31 m s^{-1} (1.12 Km hr^{-1}) is of a magnitude which could materially affect fire fighter safety.

Table 1 Parameters used in generating clustered groups of tree crowns and associated outputs.

Clump Group	N Rep	N clusters	Cluster radius	Mean total canopy fuel	Standard deviation total canopy fuel	Mean canopy cover	Standard deviation canopy cover
Not clumped	25	NA	NA	3697.2	20.3	0.82	0.01
Small	25	75	5.0	3142.0	48.6	0.57	0.04
Medium	25	25	10.0	2616.5	52.2	0.40	0.03
Large	25	5	15.0	2223.3	90.5	0.28	0.07

Table 2 Summary statistics describing forward spread rates (m- s^{-1}) by clump group. % Difference is calculated as ((max-min)/min) X 100.

Group	min	max	range	μ	σ	Median	MAD	% difference
Not Clumped	0.56	0.67	0.11	0.61	0.02	0.60	0.01	18.75
Small	0.50	0.74	0.24	0.58	0.05	0.57	0.02	48.43
Medium	0.46	0.72	0.26	0.56	0.06	0.57	0.05	57.08
Large	0.47	0.77	0.30	0.57	0.07	0.56	0.04	64.00

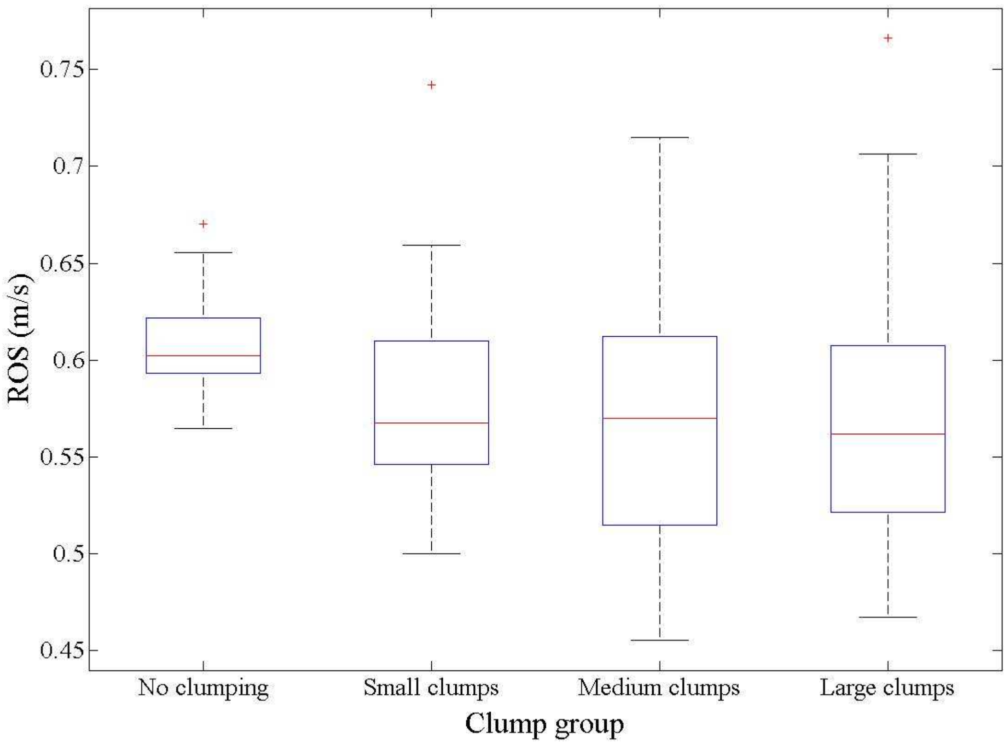

Figure 3: ROS by clump group

To gain some insights into the causes of variability in spread rate, we compared two simulations with the fastest and slowest rates of spread for the large clump group, which had the largest range in ROS. Because our comparison examines just two individual simulations out of the larger ensemble set, we emphasize here the “big picture”, first order differences, rather than going into great mechanistic detail describing fire behavior dynamics, as has been done in other work with the HIGRAD-FIRETEC model (Cunningham and Linn 2007, Linn and Cunningham 2005, Linn et al. 2005). Being members of the same clumping group the two simulations had very similar total crown fuel loads (within 3%), canopy cover (within 4%). Additionally, the spatial fuel configurations were quite similar, with scattered large clumps, and, particularly, with a gap between fuel clumps aligned with the forward direction of fire spread and proximate to the start of the FMZ. In both simulations, fire was carried by the surface fuels, but trees in the path of the fire had significant torching. In both cases, spread rates varied over time during the simulation. Despite these similarities, forward progression of the two simulated fires over time differed greatly, with a pronounced acceleration in the faster case between t=130 s and t=200 s, resulting in dramatic differences in spatial pattern and geometry of the flaming fronts as the fires evolved (**Figure 4**). The higher ROS observed in the faster case persisted until the end of the simulation. In the faster case, zonal wind velocities were channeled through the gap between the two clumps, increasing wind speeds within a small area. Despite similar size and character, the gap in the faster case had consistently higher zonal wind velocities than in the slower case (**Figure 5**). This seemingly transient behavior provided the momentum for a sustained increased spread rate which not only burned through the fuel modification zone faster, but also entered the fuels on the other side of the fuel modification zone with greater intensity. The acceleration that occurred, and its persistence in time, is not easily attributed to a single causal factor but rather arose from interactions between the fire, fuel structure and wind flow both in the immediate area of the fire and from coarser scale flow patterns at some distance from the fire. The lack of acceleration in the slower case, despite the similar gap through which such an acceleration might be expected to take place, appears to have occurred because coarser scale flow patterns contributed to strong in-drafts through that gap – effectively slowing its forward progression.

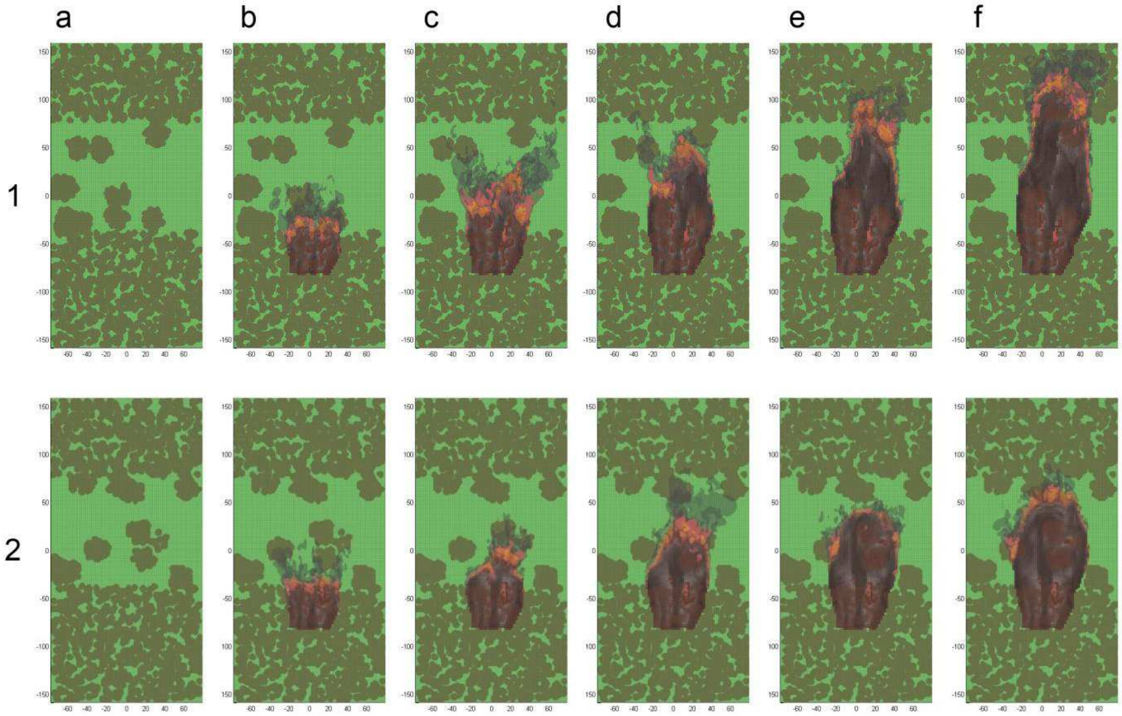

Figure 4: Comparison of fire propagation between two simulations within the same (large) clump group for the same points in time. The two simulations have identical weather inputs and fuel moistures but different spatial configurations. Differences in total canopy fuel and canopy cover between the two simulations were minimal (< 3% and < 4%, respectively).

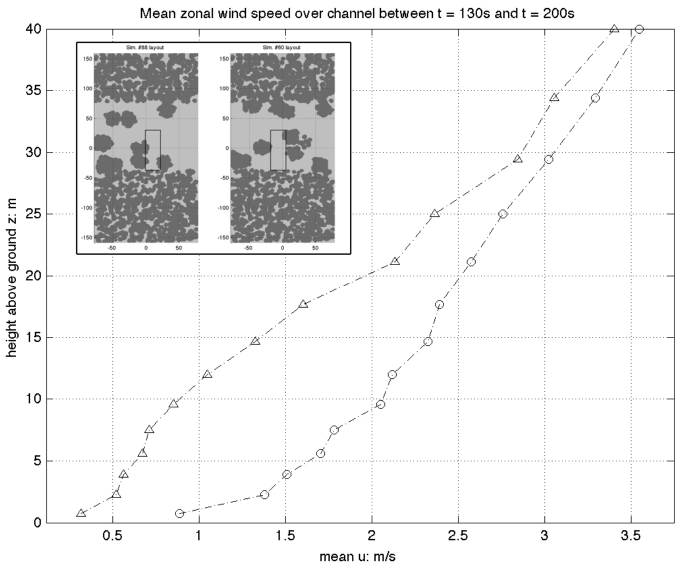

Figure 5: Comparison of time averaged vertical profile of wind speeds through gaps between tree clumps for two simulations. Two different fuel configuration replicates within the same (Large) clump group are shown above. Both have gaps between tree clumps in the immediate path of the fire as it enters the Fuel Modification Zone. Despite the similar size and character of these gaps, the wind profile for the configuration shown in left of inset figure (circle markers), significantly accelerated as winds were channelled through the gap, while the other fuel configuration (triangle markers) had a much less marked effect.

5. Discussion

We conducted a replicated numerical study which examined the effects of spatial heterogeneity in crown fuels on the forward spread rate. We found that variability in the spatial configuration of crown fuels resulted in significant variability in the forward spread rate, and that the magnitude of this variability increased with the spatial scale of heterogeneity in the fuels. Neither canopy cover, nor the total amount of crown fuel, was a reliable predictor of the forward spread rate through the fuel modification zone, largely because high variability in spread rates within clumping groups overwhelmed predictive relationships of canopy cover and total fuel. While the spatial scale of our simulation experiment, (a single stand) was finer scale than is generally significant to management, variability of the magnitude that we observed, if extrapolated to landscapes, could be quite significant, particularly for firefighter safety.

The findings of this study have important implications for the role of modeling in fire management. Despite similarities in the macroscopic spatial structure of fuels, significant differences in ROS arose, due to subtle fine-scale, dynamic interactions between the atmosphere, fuels and fire that would not be readily apparent beforehand from either aspects of the fuels (such as the total amount of fuel or the canopy cover within a stand of trees), or weather parameters (such as average wind speed), both of which are described at a coarser scale of detail. Rather, these interactions evolved over time as the fire moved through the fuels. This suggests a certain inherent lack of predictability in fire spread, particularly at fine scales. In practice, estimates of ROS are made at larger integral scales, where finer scale variability in spread rates tends to even out. This is problematic, however, because estimates of ROS made at coarser scales often include influences of different sources of heterogeneity which are not explicitly accounted for. This can compromise the degree to which ROS predictions are transferrable from one situation to another. One could argue that this was precisely the case with the data used to produce Rothermel's crown fire spread model (Rothermel 1991). Cruz and Alexander (2010) have discussed this in detail.

From a mechanistic point of view, however, this lack of predictability is a natural consequence of the complex nature of wildland fire behavior, in which numerous processes interact simultaneously across a spectrum of spatial and temporal scales. Whether the crown of an individual tree catches fire, for example, is dependent not only on the quantity and characteristics of fuel in that tree and the magnitude and geometry of the heat source near it (local influences), but also on convective heating, buoyancy induced in-drafts, canopy wind drag effects, turbulence and wind gusts occurring at some distance from the tree in question or which have occurred previously in time but which continue to influence outcomes (non-local influences). The difficulty in predicting instantaneous or local fire spread rates increases as the heterogeneity of the surrounding environment increases because of the influence of events and conditions at neighboring locations.

When the variations in fuel structure are small compared to the scales of the flame lengths, strong indrafts, and mean optical path lengths, their influence on the spread rates tend to be more continuous as the fire propagates. This is because the ensemble of influences affecting the fire at the location of interest is relatively constant. As the variations in the ensemble of influences approaches zero the variations in spread will also fall off. The result will be relatively continuous spread rates with high predictability for constant wind conditions. Conversely, when the variations in fuel structure are large compared to the length scales of processes affecting the fire, there will likely be a wide variation in the ensemble of processes that affect the fire at any point in time or space, and the nature of the ensemble of influences will tend to be more sensitive to location and configuration as well as timing and sequence of events.

Wildland fire decision support systems in the United States are currently in development which incorporate variability in weather inputs with operational models to provide more probabilistic, rather than purely deterministic, outputs. Our study complements that development by adding consideration of sources of variability that are by their nature beyond the scope of empirical operational fire models. These developments may mark the beginnings of a paradigm shift, in which greater emphasis is placed on the identification of the relative uncertainty associated with different factors and on the range of potential outcomes that might arise. The results presented here illustrate that ensemble or replicated simulations with physical fire models could be used to identify the primary sources of variability in fire spread, as well as the spatial and temporal scales at which those sources of variability tend to most affect outcomes. An improved understanding of these sources of variability and their relative impacts on fire behavior will likely be important to the development of better operational fire models.

Finally, our effort, here, in exploring variability in fire behavior with replicated numerical simulations, represents an important, but only preliminary, step. We assessed impacts of crown fuel spatial heterogeneity on spread rate, but used a homogeneous surface fuel to help isolate effects of crown fuel heterogeneity. It is likely that the variability in ROS that we observed here as a consequence of spatial crown fuel heterogeneity could be less pronounced if other sources of variability, such as surface fuel or fuel moisture variability, were also present. One of the advantages of our simulation approach is that such influences can be isolated and studied to determine their relative impact. This would not be possible for real field experiments, where heterogeneity arising from different sources can greatly complicate both outcomes and inferences of burn experiments. More work is needed to examine the nature and magnitude of variability arising from other sources, such as heterogeneity in surface fuel loads and fuel moisture, as well as a quantification of the impact of these sources under a range of atmospheric conditions.

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