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Numerical Investigation of Aggregated Fuel Spatial Pattern Impacts on Fire Behavior

Russell A. Parsons [1,*], Rodman R. Linn [2], Francois Pimont [3], Chad Hoffman [4], Jeremy Sauer [5], Judith Winterkamp [2], Carolyn H. Sieg [6] and W. Matt Jolly [1]

1 US Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, 5775 W. Highway 10, Missoula, MT 59801, USA; mjolly@fs.fed.us
2 Los Alamos National Laboratory, Earth and Environmental Sciences Division, Mail Stop: T003, Los Alamos, NM 87554, USA; rrl@lanl.gov (R.R.L.); judyw@lanl.gov (J.W.)
3 INRA, UR 629 Ecologie des Forêts Méditerranéennes, Domaine Saint Paul, Site Agroparc, F-84914 Avignon CEDEX 9, France; francois.pimont@inra.fr
4 Department of Forest and Rangel and Stewardship, Colorado State University, 1472 Campus Delivery Fort Collins, CO 80523, USA; c.hoffman@colostate.edu
5 National Center for Atmospheric Research, Research Applications Laboratory, P.O. Box 3000, Boulder, CO 80307-3000, USA; jsauer@ucar.edu
6 US Forest Service, Rocky Mountain Research Station, Forestry Sciences Lab, 2500 South Pine Knoll Drive Flagstaff, AZ 86004, USA; csieg@fs.fed.us
* Correspondence: rparsons@fs.fed.us; Tel.: +1-406-329-4872

Received: 10 April 2017; Accepted: 14 June 2017; Published: 18 June 2017

Abstract: Landscape heterogeneity shapes species distributions, interactions, and fluctuations. Historically, in dry forest ecosystems, low canopy cover and heterogeneous fuel patterns often moderated disturbances like fire. Over the last century, however, increases in canopy cover and more homogeneous patterns have contributed to altered fire regimes with higher fire severity. Fire management strategies emphasize increasing within-stand heterogeneity with aggregated fuel patterns to alter potential fire behavior. Yet, little is known about how such patterns may affect fire behavior, or how sensitive fire behavior changes from fuel patterns are to winds and canopy cover. Here, we used a physics-based fire behavior model, FIRETEC, to explore the impacts of spatially aggregated fuel patterns on the mean and variability of stand-level fire behavior, and to test sensitivity of these effects to wind and canopy cover. Qualitative and quantitative approaches suggest that spatial fuel patterns can significantly affect fire behavior. Based on our results we propose three hypotheses: (1) aggregated spatial fuel patterns primarily affect fire behavior by increasing variability; (2) this variability should increase with spatial scale of aggregation; and (3) fire behavior sensitivity to spatial pattern effects should be more pronounced under moderate wind and fuel conditions.

Keywords: fuel; spatial heterogeneity; canopy cover; fire behavior; variability; FIRETEC

1. Introduction

Heterogeneity is an integral characteristic of natural systems, influencing species distributions, their interactions, and their fluctuations in time and space [1]. In forested ecosystems, fine-scale heterogeneity influences resource availability and conditions for growth, such as snow storage [2], and light availability [3]; such patterns, as well as interactions between individual trees, influence growth rates and stand dynamics [4]. Perhaps one of the most important roles of heterogeneity, however, is in moderating and regulating disturbances such as fire; in many ecosystems, heterogeneous patterns in fire severity lead to patchy or aggregated regeneration patterns which then modify the spread and intensity of subsequent fires [5–8] and which foster variability in fire effects [9,10]. Such interactions

between pattern and process are a fundamental concern in the study of landscape dynamics [11]. While mixed or stand-replacing fire regimes are often characterized by larger scale patches [8,12], dry, fire-frequent forests such as ponderosa pine (*Pinus ponderosa*) and dry mixed-conifer systems in the western United States, are more associated with fine-scale heterogeneity, historically consisting of fairly low-density forests, with canopy cover of 25–30% [13] and characterized by mosaics of individual trees, clumps of trees with interlocking crowns, and openings [14,15]. Reconstructive studies of forest structure and stand dynamics suggest that this diverse spatial structure arose, and was maintained over time, as a result of the interactions between disturbances (primarily fire, insects, and windthrow) and patches of regeneration which followed those disturbances [14]. Both insects and windthrow tend to affect forests in clumpy patterns, often resulting in local concentrations of dead and downed wood which, when exposed to subsequent fires, tend to burn longer, producing coherent swaths of bare mineral soil favorable to subsequent seedling establishment. The long-term historical persistence of these mosaics in the face of natural climatic variability [16] suggests a system with substantial resilience [17], in which responses to frequent perturbations maintain a stable equilibrium [18].

Over the last century, however, this resilience has eroded in many forest ecosystems, as fire suppression and shifts in other land use practices [19] have led to more homogeneous and higher density stand structures [4,20–22], with canopy cover often 50–60% or higher [13]. These shifts, as well as climate change impacts, have resulted in altered fire regimes, with substantial increases in the number of wildland fires, area burned, and fire severity relative to the 20th century [23–25]. Several intense fires of unprecedented size in dry forest types in recent years have been linked to denser and more homogeneous forest structures [26,27]. In addition to coarse-scale changes in fire regimes, this increasing homogeneity is considered a factor in recent insect outbreaks that have occurred at unprecedented scales [28]. These widespread shifts have led to federal policies supporting fuel treatment strategies to mitigate catastrophic fires and restore ecosystem function [29,30]. While many such efforts have not considered spatial heterogeneity, there is increasing awareness of the need for fuel treatment strategies which attempt to restore ecosystem resilience and modify fire behavior by increasing fine-scale heterogeneity with clumpy or aggregated fuel spatial patterns [31–35].

While a number of studies have shown that fuel treatments can be effective in decreasing fire intensity [36–38], particularly within treated stands, many questions remain [38], particularly with regard to the scale at which fuel treatments must be applied to be effective. At landscape scales, where fuel treatments are considered most important [17], the proportion of landscape area that must be treated to be effective can be a significant limitation, even when applying strategic approaches that leverage greater overall effects [39,40]. An additional complication is that fuel accumulation and vegetation growth following treatment tends to reduce treatment effectiveness over time [41]; in many cases this window of opportunity may pass before a treatment is tested by a fire [42,43]. Other studies suggest that fuel treatments are less effective under more extreme weather conditions [44]. These factors contribute to considerable uncertainty regarding the effectiveness of fuel treatments at landscape scales.

Many questions remain regarding fuel treatment effectiveness even at stand scales [38]. While ecologists have provided fairly detailed guidance regarding desired stand heterogeneity [14,17,45], at present, it is difficult to predict how such guidelines will modify fire behavior, such as reducing fire intensity or rate of spread, or achieve desired fire effects, such as limiting mortality in certain species or size classes of trees. Similarly, it is difficult to anticipate the sensitivity of fuel treatment effectiveness under different environmental conditions, such as wind speeds. An additional source of uncertainty arises from the fact that fuel treatments often alter the microclimate within a stand, potentially altering seedling growth conditions [46], as well as wind speeds [47], or fuel moisture [48], with potential feedbacks to fire behavior [49]. Ideally, such questions could be resolved with stand-scale field fire experiments. However, in addition to the cost and logistical difficulties with such experiments, real world stands can only be burned once, and differences between sites and burning conditions can often complicate inferences across experiments [43]. Due to these limitations, modeling plays a key role in attempting to answer these questions. While modeling is always an abstraction of reality,

well-constructed modeling studies offer a complementary perspective to field studies [50], in which the same stands can be burned across a range of conditions, and different sources of variability can be isolated and their effects identified.

Unfortunately, many of these issues are difficult to resolve with commonly available tools used to model forest dynamics and fire behavior [51], primarily due to limitations in the underlying fire models [52,53], which do not consider fine-scale spatial heterogeneity and thus are constrained to represent average stand conditions. The wide use of these tools despite these limitations tends to reinforce an aspatial perspective [14,54]. This reduced detail often results in relatively low sensitivity in changes in predicted fire behavior, particularly with respect to surface fuels, despite the fact that such fuels are often greatly altered by fuel treatments [55]. Similarly, a number of issues have been identified in certain key outputs of systems commonly used in evaluating fuel treatment effects on fire behavior [56]. While these systems continue to be widely used and are still applicable to many situations, such limitations complicate efforts to evaluate the effects of fine-scale heterogeneity patterns on the processes of fire behavior.

In recent years, however, advances in computational capabilities and in numerical modeling have led to the development of physics-based fire behavior models which are capable of examining fuel-fire interactions with greater detail [57–60]. With three-dimensional computational domains, spatial resolution of a few meters or less, and temporal resolution often finer than 1 s, these models are capable of representing fine-scale fuel heterogeneity, both for trees and surface fuels, with great detail, as well as critical interactions between fire and fuels, fire and atmosphere, and fuels and atmosphere [59]. Key effects modeled include drag from the canopy on the wind field, radiative and convective heat transfer, dynamic plume development, and radiative shielding, in which radiative heat transfer may be impeded by the presence of tree crowns or other obstacles. These dynamic interactions comprise a key difference between physics-based models and more commonly used semi-empirical fire models and provide for a range of emergent behaviors that can provide insights into numerous aspects of fire behavior.

Several recent studies with such models examining effects of fine-scale aggregated fuel patterns on fire behavior provide varying perspectives. Linn et al. (2002) [58] found that thinned forests had faster effective wind speeds due to reduced drag within the stand, as well as higher rates of fire spread; and aggregated fuel patterns resulted in higher rates of spread than more random fuel distributions. Hoffman et al. (2012) found that aggregated fuel patterns resulted in increased fire intensity relative to random or homogenous fuel patterns [61]. In contrast, Pimont et al. (2011), found little effect on mean fire intensity or rate of spread, although variability in the wind field increased with clump size [62]. Most recently, Ziegler et al. (2017) examined seven different real world fuel treatments intended to restore historical patterns of fine-scale heterogeneity [63]. Across a range of wind speeds, they found that all such treatments reduced fire rate of spread and fire intensity, regardless of spatial heterogeneity, but that canopy fuel consumption in treated stands was unaffected by increases in wind speed. As this latter study was based on spatially explicit forest inventory data, each case is unique, with different pre- and post-treatment forest composition, structure, stand densities, canopy and surface fuel loads, and spatial patterns. While this diversity is of course representative of real world forests, variability within and between stands, both horizontally and vertically, as well as in other factors, makes it difficult to isolate effects of different potential drivers. Synthesizing results across this and other previous modeling experiments, the overall message is somewhat difficult to interpret; in some cases, fuel treatments increased rates of spread, while others resulted in decreases. Similar divergent outcomes arise with respect to fire intensity. Some studies reported higher variability associated with aggregated fuel patterns while others showed little sensitivity. These independent studies were carried out with different objectives in mind, and in different sites, so they should not be expected to definitively answer broader questions. However, collectively, they suggest the need for investigations that isolate different sources of variability and facilitate exploration of the sensitivity of different factors. A few key questions remain unanswered: (1) how do treatments with aggregated

spatial patterns affect mean fire behavior outcomes? (2) how do such treatments affect variability in fire behavior? (3) if there are effects, do they change with spatial scale of aggregation? and (4) are such effects sensitive to wind speed or canopy cover?

In the present study, we set out to develop a process by which we could explore the effects of spatial fuel heterogeneity on fire behavior while isolating specific sources of variability. Our controlled experiment had two objectives, relating to the questions posed above: (1) to assess the impacts of spatially aggregated fuel patterns on the mean and variability of stand-level fire behavior; and (2) to explore potential effects of wind and canopy cover on the relationship between fuel pattern and fire behavior. To accomplish these objectives, we generated a series of fuel maps representing combinations of two levels of forest canopy cover (60% and 30%), and three different forest spatial patterns with increasing levels of aggregation (low, moderate, and high), each stochastically replicated twice to provide paired cases that differ only in spatial pattern. To isolate horizontal spatial pattern as the primary variable of interest, we eliminated between-tree variability, using identical modeled trees, and used the same vertical fuel distribution in all cases. The use of identical trees and identical vertical fuel distributions ensured that all cases of a given canopy cover had exactly the same fuel loads. Thus, in this abstracted forest simulation study, canopy cover serves as a proxy for fuel load. To test sensitivity to environmental conditions, we simulate fire in each fuel map case at two wind speeds. As an exploratory study, our experiment seeks to provide insights potentially leading to new hypotheses and to identify wind and fuel scenarios where spatial heterogeneity impacts on fire behavior may be greatest and thus warrant more in-depth investigation in subsequent work.

2. Materials and Methods

2.1. Numerical Model

FIRETEC is a coupled atmospheric/wildfire model based on conservation of mass, momentum, energy, and chemical species [57]. A key coupling arises primarily from a buoyancy term in the fully compressible, three-dimensional Navier-Stokes equations comprising the governing equation set of the atmospheric dynamics component (HIGRAD) [64]. Atmospheric dynamics additionally couple with the fire/fuels component (FIRETEC), primarily through drag forces acting on fuels, convective heat exchange, and advection/turbulent mixing of oxygen. As the formulation of the model has been presented in previous work [57] we focus here on the numerical experiment carried out for this study. Models such as FIRETEC allow systematic study of the effects of changing specific conditions without changing other conditions, whereas this is difficult to achieve in field observations. The capacity of physical process-based models such as FIRETEC to explore complex interactions between fuel properties, the atmosphere, and dynamic fire behavior facilitates new insights, which may lead to new hypotheses.

2.2. Numerical Configuration

We simulated a flat, rectangular domain, measuring 480 m in x and 384 m in y (~18.4 ha). Within this area, regions on both ends of the domain, extending from x = 0 to x = 80, and from x = 432 to x = 480, were identical for all simulations, and populated with canopy fuels from the low aggregation case (described below). Canopy fuels and associated surface fuels, described below, were modified to have different levels of spatial aggregation in the middle region of the simulation domain (from x = 80 to x = 432) (Figure 1). Numerical grid resolution represents a compromise between greater detail, computational costs, and intended scale of application. To be feasible at landscape scales with fairly large domains, FIRETEC represents combustion as a relatively simple sub-grid mixing-limited process, assuming that turbulent mixing scales are small compared to the grid resolution. Thus, FIRETEC is typically run with horizontal resolution of 2 m, while vertical resolution (z) increases with height following a cubic polynomial function, ranging between 1.5 and 5.6 m within the canopy. The model has been most widely used and evaluated with this resolution, which is adequate to represent fuel

heterogeneity and to model flow fields in the present study. Simulations required roughly 3000 CPU hours including the development of wind fields and fire simulation. Specific runs took less time or more time depending on wind speed.

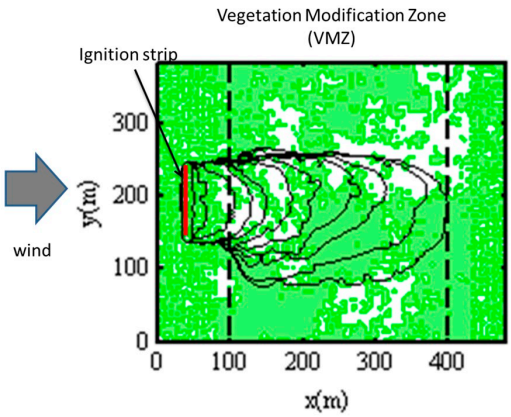

Figure 1. Schematic diagram of the simulation domain with an example simulated forest pattern (green), and an example fire, represented as a series of perimeter contours. The simulation domain measures 480 m in *x* and 384 m in y. Wind enters the domain from the left side of the figure and proceeds to the right. After initial wind field development, a fire is initiated at the location of the ignition strip. Fire metrics used in analysis are calculated over the 300 m length between x = 100 m and x = 400 m.

2.3. Canopy and Surface Fuels

Forest canopies can be represented in many ways and with different levels of detail [65], ranging from homogeneous patches [44] to heterogeneous individual tree crowns [66,67]. For simplicity and ease of replicability, in this study, to eliminate between-tree variability, all tree crowns were identical and represented as homogeneous rectangular volumes, 4 m on a side and 10.2 m long. Fuel properties were derived from the average of overstory ponderosa pine trees intensively measured and destructively sampled in the Ninemile area of the Lolo National Forest in western Montana [68]. To provide a realistic vertical structure, crown base heights followed a normal distribution with mean of 14.2 m and standard deviation of 3.30 m. The bulk density of each tree crown volume was set to 0.124 kg m^{-3}, corresponding to 20.2 kg combined dry weight of canopy fuel (all foliage and one half the fine woody fuels of 6 mm or less in diameter) [68]. Such a bulk density in discrete fuels would lead to the stand-level bulk density (0.089 kg m^{-3}) reported by [68] assuming a 70% cover. In the present study, we simulated canopy cover of 30% and 60%. The 60% cover corresponds to a canopy fuel load on the same order as described in [68], and the 30% cover corresponds to a similar forest after removal of half the trees by thinning.

For simplicity, surface fuels were coupled with the presence or absence of canopy fuels above them, with litter under trees and grass in open areas. Litter fuels were characterized with a depth of 0.032 m, bulk density of 22.4 kg m^{-3}, and fuel load of 0.717 kg m^{-2} [69]; and grass fuels were described with a depth of 0.3 m, bulk density of 1.40 kg m^{-3}, and fuel load of 0.420 kg m^{-2} [69]. Surface area to volume ratio was 5760 m^{-1} for litter and 6860 m^{-1} for grass [70]. Fuel moistures for both litter and grass were 6%, consistent with fuel moisture conditions commonly associated with active crown fire.

One of the challenges in examining interactions between forest structure and fire is that numerous sources of heterogeneity can influence outcomes. For example, voxelization of trees in point patterns to grids can result in variability in fuel density, as parts of multiple trees can each contribute fuel to a given cell. To facilitate exploration of effects of cover and pattern on fire, it was necessary to eliminate some of these sources of variability. Our use of identical tree crowns eliminated between-tree variability and

ensured identical vertical fuel distributions for a given canopy cover case. We eliminated variability in fuel density by developing a process for generating spatial patterns, described below, which placed the tree crowns and associated surface fuels (described above) as non-overlapping volumes, aligned horizontally with the computational grid. This ensured that our synthetic forests of a given canopy cover would have exactly the same fuel quantities when considered over the vegetation modification zone, such that the only differences between them would be horizontal spatial patterns.

We generated spatial patterns using an Inverse Discrete Fourier Transform (IDFT) to simulate a 1/f noise process [71], which results in continuous surfaces characterized by a power spectral density of the form:

$$S(f) \propto 1/f\hat{}\alpha, \quad (1)$$

where f is frequency, and $0 < \alpha < 2$. Varying α offers a simple way to produce surfaces ranging from very rough or uncorrelated (white noise, or purely random, $\alpha = 0$) to very smooth, auto-correlated surfaces (Brownian noise, $\alpha = 2$). Between these two extremes is pink noise ($\alpha = 1$), with intermediate autocorrelation, which is extremely common in numerous natural processes [72,73], including vegetation patterns [74]. Using this approach, we generated six continuous surfaces, each with 2 unique cases (replicates), for each of three levels of spatial aggregation (α = [0, 1 or 2]). We then thresholded each continuous surface twice, retaining first 60% and then 30% of the cells, to produce maps with either 60% or 30% forest cover. This use of the same underlying pattern for both maps ensures a consistency in heterogeneity between each 60% and 30% canopy cover pair, likely reducing differences in outcomes that could arise from wholly different patterns. To minimize differences in initial conditions between different simulations, unique spatial patterns were confined to the central part of the domain, with identical fuel maps characterized by white noise (random or no aggregation, $\alpha = 0$) at both ends of the domain (Figure 1). Our fuel cases thus included 12 coupled fuel maps, spanning two unique cases each for three levels of spatial aggregation and two forest cover cases, with associated surface fuels.

2.4. Simulation of Wind Fields

We simulated fire for each fuel map with two different open wind speeds in which crown fires have been observed [56]: 6.2 m s^{-1} (moderate) and 8.33 m s^{-1} (high). Velocities were specified for 10-m above the top of the canopy (37 m), or 47 m above the ground surface, according to common protocols [75]. Wind fields were developed using Large Eddy Simulations with cyclic boundary conditions and a pressure gradient forcing [76]. Separate wind fields were developed for each combination of wind speed and canopy cover, using the low-aggregation fuels case (randomly placed trees) throughout the domain. These pre-developed wind fields provided heterogeneous initial conditions, as well as dynamic and heterogeneous boundary condition winds where the wind profiles and resolved turbulence (fluctuations in the wind field) upstream of the fire were consistent with respective fuels and winds as in Cassagne et al. (2011) [77]. Fires were ignited with a 100 m long fireline located 100 m downwind from the inlet boundary of the non-periodic, fire simulation domain. Simulations were allowed to continue until the fire was affected by the outflow boundary.

2.5. Analysis

The dynamic nature of fire behavior, particularly in the context of heterogeneous fuel spatial patterns, makes it challenging to interpret. We analyzed fire behavior both qualitatively and quantitatively. Qualitative analyses consisted of three complementary views, showing different aspects. First, we generated perimeter contours over time, computed from surface fuel consumption in order to provide an intuitive, but qualitative view of fire progressions over time. Second, to illustrate how the fire interacts with both the vegetation and the wind field, we extracted a horizontal slice of the wind field (at a height of 9.6 m) for a single simulation (moderate winds, high spatial aggregation) at four points in time (t = 160 s, 200 s, 240 s and 280 s). Third, we extracted contours over time for

both the surface fire and fire at the base of the canopy. We developed animations of these surface and canopy fire perimeters and produced plots of these contours at two points in time (t = 150 and 240), for both medium and high wind cases.

Our quantitative analysis consisted of calculation of several metrics to assess differences in fire behavior between simulations. We first calculated four metrics capturing overall global fire behavior and geometry: rate of spread in the *x* direction (Forward ROS), rate of spread in the *y* direction (Lateral ROS), fire-front intensity and burn-area growth rate. Forward ROS was calculated as a 300 m travel distance (between x = 100 m and x = 400 m) (Figure 1), divided by the travel time (time for the fire to travel between x = 100 m and x = 400 m). Similarly, lateral spread rate was calculated as the average change in the lateral (crosswind) extent of the fire divided by the travel time. Fire front intensity (FFI) (kW m^{-1}) was estimated as the average energy release rate within a virtual 20 m moving band centered on the head of the fire. Burn area growth rate was calculated as the increase in area during the time it took the fire to travel the 300 m length, divided by travel time (m^2 s^{-1}).

In addition to the global fire metrics described above, we calculated vertical profiles for two important statistics, each spatially averaged over the vegetation modification zone and temporally averaged over the time period during which the fire passed through that region. These statistics capture ambient effects as well as interactions with the canopy and the fire itself. The first such quantity was $\overline{U}$, a wind field statistic that describing the mean wind velocity in the streamwise (x) direction at each height level (m s^{-1}). The second quantity was the kinematic heat flux, $\overline{W\prime\theta\prime}$. Although rarely mentioned in wildland fire science, this measure is commonly used in the atmospheric sciences, where it describes the turbulent transport of thermal energy [78]. In the context of a fire, positive values of kinematic heat flux are associated with both hot air rising from the fire, and cooler (higher momentum) air descending from above, typically as in-drafts replacing the rising hot air. Therefore positive kinematic heat flux implies a positive atmospheric feedback on fire behavior, namely the atmospheric response to the fire itself is one that in turn tends to promote sustained or even increased fire behavior. This metric is thus related to fire intensity but more directly characterizes fire/atmosphere interactions with respect to the presence and sustainability of intense fire behavior. It is expressed in Kelvin and velocity (K-m s^{-1}). Vertical profiles of variables such as these metrics provide a view of how quantities change with height, and are useful in understanding fire/atmosphere interactions such as occur in wildfires. Along with the other metrics, described above, we included these variables in statistical analysis, described below.

We analyzed simulation outputs for each of the six fire behavior metrics using a generalized linear mixed modeling procedure (PROC GLIMMIX) using the SAS statistical analysis software. Effects of forest cover, wind and canopy spatial pattern, as well as possible statistical interaction effects were analyzed. We used a Tukey adjustment in least squares means multiple comparisons. This basic statistical analysis provided a macroscopic view of the potential significance of different factors. Probability values (-values) indicate the likelihood of a statistically significant relationship as measured against a set probability, referred to as α, typically set at 0.05. F-values are a simple measure of effect size, with large values indicating greater effect. To provide a straightforward assessment of the effects of changes in fire behavior between canopy cover cases, we calculated percent changes for all metrics. Finally, we assessed differences between results for spatial replicate pairs as a measure of the effects of aggregation on fire behavior metrics.

3. Results

Our 1/f noise process enabled us to stochastically generate unique fuel map patterns that, for a given canopy cover level, only differed in the level of horizontal aggregation, controllable by a single parameter. Higher aggregation cases had larger coherent forest and open patches (Figure 2).

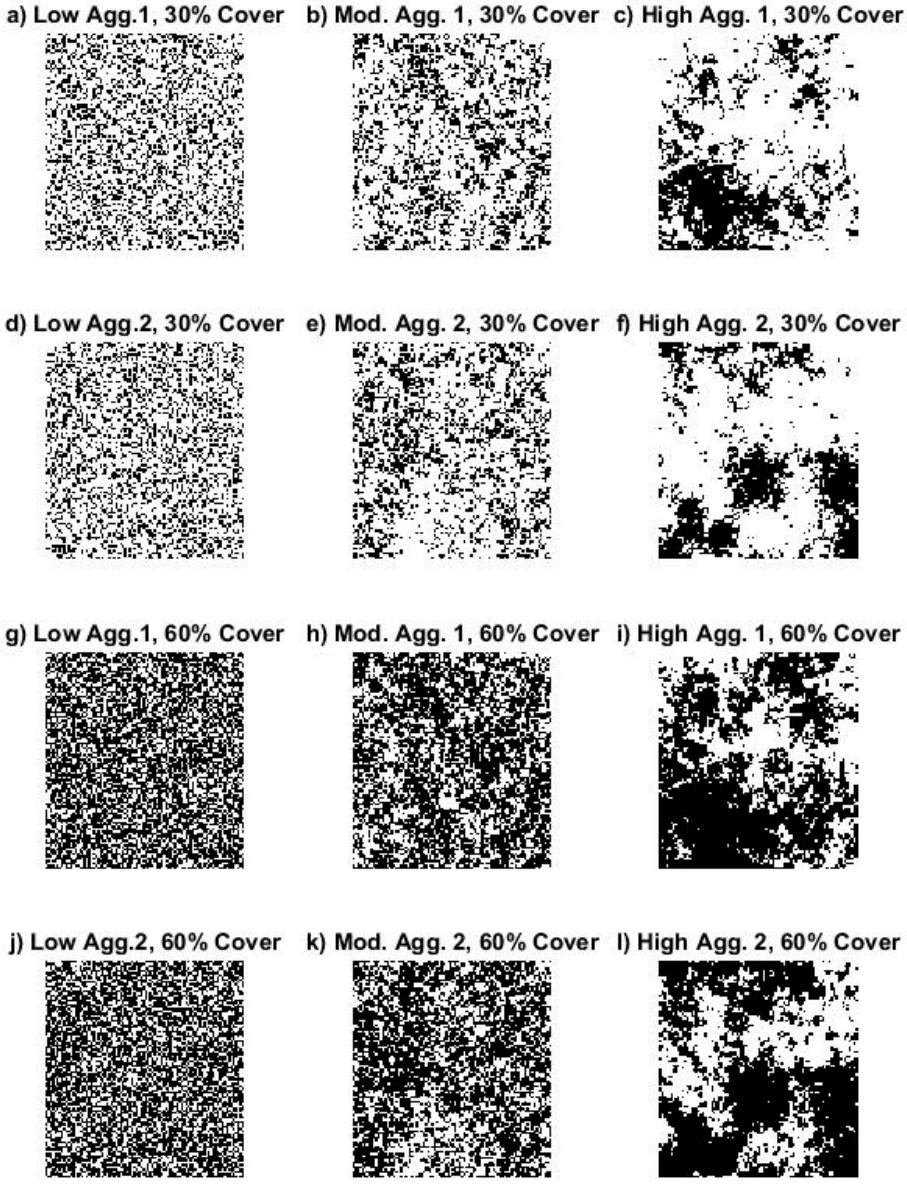

Figure 2. Synthetic coupled fuel spatial patterns generated with a 1/f noise process to represent heterogeneity in forest cover and pattern. Square areas are the central portions of the simulation domain, called the vegetation modification zone (VMZ). Vegetation patterns on either side of the VMZ were identical for all simulations for a given canopy cover case. Black cells represent forest with litter surface fuels, while white cells represent open areas with grass surface fuels. Rows from top to bottom show spatial patterns with increasing aggregation (top: low, middle: moderate, bottom: high). Within each row there are two spatial replicates, 1 and 2, each with 60% and 30% canopy cover cases; 30% canopy cover cases are derived from corresponding 60% canopy cover cases.

Interactions between fuel spatial patterns, winds, and fire influenced the timing and geometry of fire spread, illustrated for all fuel maps for the medium wind cases as contours (Figure 3). Differences in fire behavior between the 60% and 30% canopy cover cases are clear, particularly in lateral spread; qualitatively, contour shapes and sequence seem more regular when cover is high and aggregation is low, and larger scale aggregation seems to affect fire trajectories and result in more erratic spread (Figure 3).

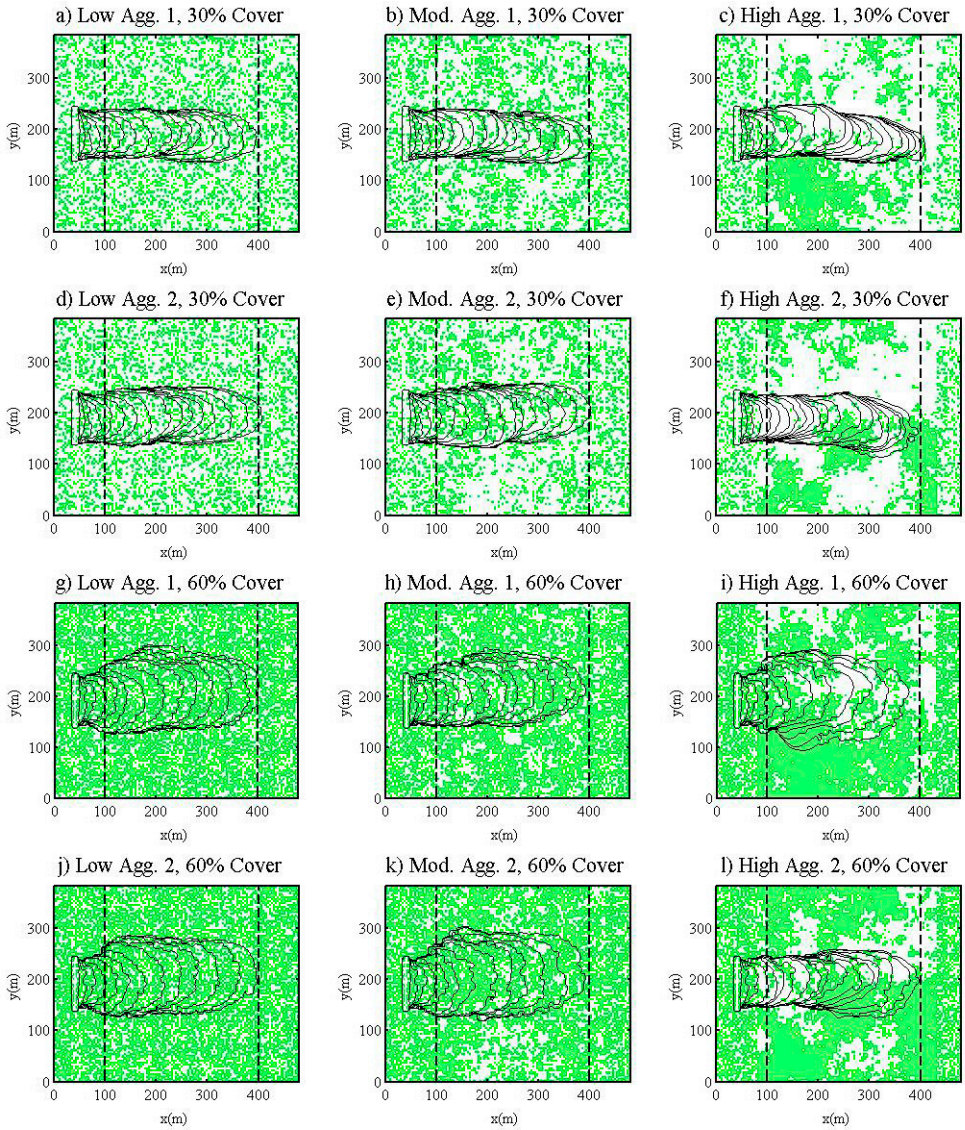

Figure 3. Maps of coupled fuel spatial patterns, with forest/litter in green and grass as white, overlaid with contours indicating progression of fires over time with moderate winds (6 m s^{-1} 10 m open wind speed). Fuel maps span three levels of aggregation (low, left, to high, right), and two levels of canopy cover (upper two rows: 30%; lower two rows: 60%).

Quantitative metrics calculated for fire simulations are presented in Table 1. Statistical analysis results are summarized in Table 2, which provides F-values and *p*-values indicating effect size and statistical significance, respectively, for the three factors (canopy cover, wind, and spatial aggregation) for each of the six fire behavior metrics (forward ROS, lateral ROS, fire front intensity, area growth rate, $\overline{U}$, and $\overline{W\prime\theta\prime}$). Significant *p*-values at $\alpha \leq 0.05$ are shown in bold, while those that are potentially significant at $\alpha \leq 0.1$ are shown in italics.

Table 1. Fire behavior metric outputs for simulations spanning two wind speeds, two levels of canopy cover, and three spatial patterns with different levels of aggregation, each with two replicates. For each simulation, results for six metrics are presented: Forward ROS (m s^{-1}), Lateral ROS (m s^{-1}), Fire front intensity (kW m^{-1}), Area growth rate, $\overline{U}$ (m s^{-1}), and $\overline{W'\theta'}$ (K-m s^{-1}). The table has fire metrics for medium wind speed cases (top rows) and high wind speed cases (bottom rows).

Aggregation	Canopy Cover (%)	Wind (m s^{-1})	Spatial Rep.	Forward ROS (m s^{-1})	Lateral ROS (m s^{-1})	FFI (kW m^{-1})	Area Growth (m^2 s^{-1})	$\overline{U}$ (m s^{-1})	$\overline{W'\theta'}$ (K-m s^{-1})
High	30	6	1	1.07	0.01	9937	90.72	1.926516	2990.816
High	30	6	2	0.94	0.05	16435	102.9	2.208445	1721.743
High	60	6	1	1.5	0.3	30144	304.37	1.888608	8181.061
High	60	6	2	1.25	0.1	23260	146.52	1.305603	3523.89
Mod.	30	6	1	1.25	0.01	16714	108.91	1.996807	3017.719
Mod.	30	6	2	1.25	0.04	20152	149.19	2.221115	4228.264
Mod.	60	6	1	1.25	0.13	31443	203.79	1.510659	6228.22
Mod.	60	6	2	1.88	0.21	37025	276.3	1.834218	7694.21
Low	30	6	1	1.25	0.01	19263	126.14	2.056256	4674.78
Low	30	6	2	1.5	0.02	18553	146.31	2.024153	4118.357
Low	60	6	1	1.5	0.18	33730	224.38	1.627666	7364.256
Low	60	6	2	1.88	0.16	34516	252.66	1.622371	7606.724
High	30	8	1	1.5	0.13	19153	217.36	2.939569	3512.493
High	30	8	2	1.5	0.08	17727	173.78	3.178108	1569.894
High	60	8	1	1.88	0.43	41513	396.69	2.271007	12410.23
High	60	8	2	1.88	0.27	32660	309.29	2.20966	7430.328
Mod.	30	8	1	1.5	0.03	21545	149.2	2.876069	2326.597
Mod.	30	8	2	1.5	0.09	24950	203.54	3.151718	3052.377
Mod.	60	8	1	1.88	0.33	50365	366.87	2.31237	10256.37
Mod.	60	8	2	1.88	0.32	45349	344.91	2.517559	12297.55
Low	30	8	1	1.5	0.05	21997	186.5	2.967419	3660.467
Low	30	8	2	1.5	0.05	21272	192.43	2.919022	3347.423
Low	60	8	1	1.88	0.38	49021	376.66	2.456716	12747.55
Low	60	8	2	2.14	0.37	45969	369.7	2.347026	11841.7

Table 2. Summary of results of statistical analysis using a generalized linear mixed modeling procedure (PROC GLIMMIX) with the SAS statistical analysis software. Effects of forest cover, wind and canopy spatial aggregation, as well as possible interaction effects were analyzed.

Factor –>	Canopy Cover		Wind		Aggregation				
Variable	F value	Pr > F	F value	Pr > F	F value	Pr > F	Interactions?	F value	Pr > F
Forward ROS	31.28	<0.0001	24.52	0.0002	3.03	0.0807	None	–	–
Lateral ROS	92.61	<0.0001	23.33	0.0003	0.48	0.6303	CC X Wind	7.24	0.0175
Fire Front Intensity	218	<0.0001	42.49	<0.0001	12.84	0.0007	CC X Wind	10.2	0.0065
Area Growth Rate	72.77	<0.0001	32.6	<0.0001	0.33	0.7272	None	–	–
$\overline{U}$	63.03	<0.0001	144.17	<0.0001	0.3	0.7445	None	–	–
$\overline{W'\theta'}$	88.72	<0.0001	9.84	0.0073	2.73	0.0998	CC X Wind	16.23	0.0012

Our results indicate that canopy cover and wind were positively related to forward ROS, area growth rate, and $\overline{U}$ ($p \leq 0.001$). However, for lateral ROS, fire front intensity, and $\overline{W'\theta'}$, our results suggest that there are some statistically significant interaction effects between canopy cover and wind ($p \leq 0.01$), indicating that outcomes are dependent on both factors, and do not respond the same way in all situations. For fire front intensity and $\overline{W'\theta'}$, our results show that the effect of canopy cover is reduced in higher wind versus lower wind scenarios, while the effect of canopy cover on lateral rate of spread increased only under the high wind scenarios. Regardless of wind speed, both lateral rate of spread and fire front intensity were lower at 30% cover than at 60% cover. However, under 30% cover, there was no effect on lateral rate of spread or fire front intensity due to wind speed, but at 60% cover, lateral rate of spread was higher at high wind speeds than at low wind speeds. The effects of aggregation on area growth rate, lateral spread, and U velocity were not significant ($p > 0.05$). However, we did find a negative relationship between the level of aggregation and the fire front intensity ($p = 0.0007$). Although not significant at $\alpha = 0.05$, our results also indicate that there

was a negative relationship between aggregation and the kinematic heat flux ($\overline{W'\theta'}$) near canopy base height ($p = 0.0997$), as well as with forward rate of spread ($p = 0.0807$), which are both closely related to fire front intensity.

As canopy cover and wind were the strongest drivers of changes in all fire metrics, we organized the data as percent change in fire metrics occurring between 60% cover cases and 30% cover cases, by wind speed (Table 3), providing a more intuitive view of our simulation results (Figure 4).

Table 3. Percent change in fire behavior metrics, shown in Table 1, from 60% forest cover to 30% forest cover, for each of six metrics. Each metric is represented with two columns in which the left shows percent changes for medium wind cases and right shows percent changes for high wind cases. The left most column, "Agg.", is an abbreviation of "aggregation" or scale of forest canopy clumping.

Agg.	$\overline{u}$	$\overline{u}$	ROS dx	ROS dx	ROS dy	ROS dy	FFI	FFI	Area Growth	Area Growth	$\overline{W'\theta'}$	$\overline{W'\theta'}$
	Wind 6 m/s	Wind 8 m/s	Wind 6 m/s	wind 8 m/s	wind 6 m/s	wind 8 m/s	wind 6 m/s	wind 8 m/s	wind 6 m/s	wind 8 m/s	wind 6 m/s	Wind 8 m/s
Low	26.3	20.8	−16.7	−20.2	−94.4	−86.8	−42.9	−55.1	−43.8	−50.5	−36.52	−71.28
Low	24.7	24.4	−20.2	−29.9	−87.5	−86.5	−46.2	−53.7	−42.1	−47.9	−45.86	−71.73
Mod.	32.2	24.4	0.0	−20.2	−92.3	−90.9	−46.8	−57.2	−46.6	−59.3	−51.55	−77.32
Mod.	21.1	25.2	−33.5	−20.2	−81.0	−71.9	−45.6	−45.0	−46.0	−41.0	−45.05	−75.18
High	2.0	29.4	−28.7	−20.2	−96.7	−69.8	−67.0	−53.9	−70.2	−45.2	−63.44	−71.70
High	69.2	43.8	−24.8	−20.2	−50.0	−70.4	−29.3	−45.7	−29.8	−43.8	−51.14	−78.87
Mean	+29.3	+28.0	−20.6	−21.8	−83.6	−79.4	−46.3	−51.8	−46.4	−48.0	−48.93	−74.35
Stdv.	22.1	8.23	11.7	4.0	17.4	9.7	12.1	5.1	13.2	6.5	8.95	3.26

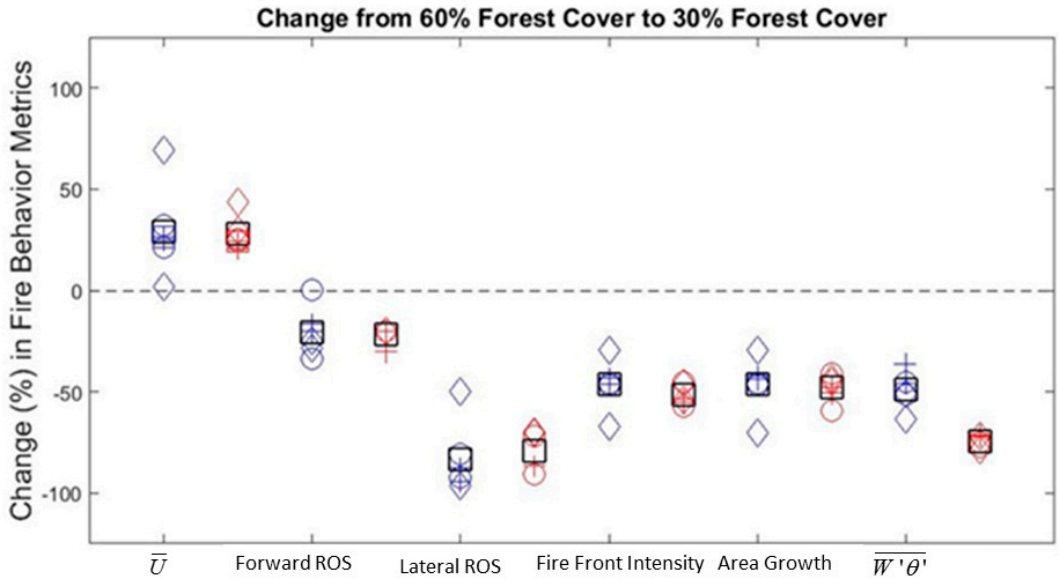

Figure 4. Changes in wind speeds and several fire behavior metrics, expressed as percent change between 60 and 30% canopy cover cases. Blue colors depict moderate wind cases while red depict high wind cases. Three spatial patterns are represented: low aggregation with a plus sign symbol, moderate aggregation with circles, and high aggregation as diamonds. For any plot column, mean percent change is shown with open bold outlined black squares.

Reduction in canopy drag between the 60% and 30% canopy cover cases resulted in increased mean streamwise velocities ($\overline{U}$, Figure 4). Mean increase in wind was very similar between medium and high wind cases, with increases of 29.3% and 28.0% (Table 3, Figure 4). Despite increased wind speeds with lower cover, all metrics of fire behavior were reduced significantly. Average reductions across different spatial patterns ranged from about 20% reduction in forward spread rate, to around 80% reduction in lateral spread rate and in $\overline{W'\theta'}$. The range between spatial aggregate replicate pairs

(similar symbols in the same column) appears to increase with aggregation, with more pronounced differences between high aggregation cases. In the following few paragraphs, we present results that provide some insights regarding why variability in fire behavior appears to increase with larger scale spatial aggregation.

A key aspect of fire behavior in these simulations is the fire- and canopy-influenced wind field (Figure 5).

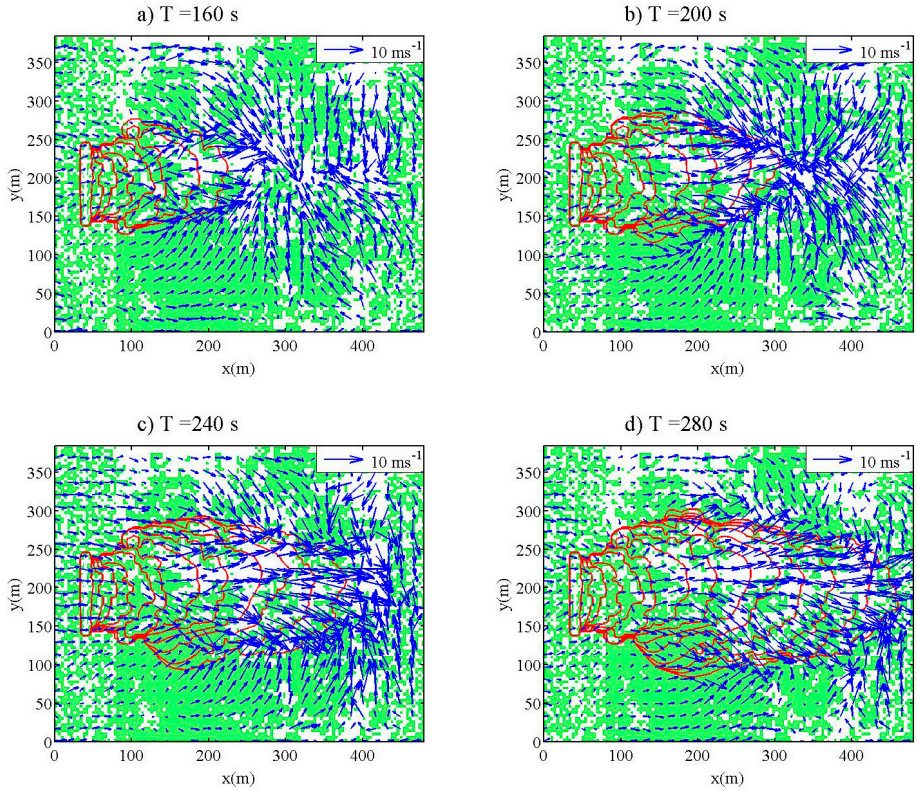

Figure 5. Overhead perspective showing the progression of a single fire, as red fire perimeter contours, in a spatially heterogeneous forest, at four different points in time (t = 160 s (**a**), 200 s (**b**), 240 s (**c**), and 280 s (**d**)). Blue arrows indicate wind field direction and magnitude (longer arrows indicate higher local wind speeds), at a height of 9.6 m above the ground. This figure illustrates complex and dynamic interactions between the wind field, the canopy, and the fire over time. Winds coming into the fire at the fire front are typically convective in-drafts.

Wind flow responds to interactions between the vegetation and the fire in several ways. Drag from the canopy forces wind to flow through gaps in the vegetation, with perturbations in the flow field typically similar in spatial scale to heterogeneity within the vegetation. The degree of interaction of these perturbations with the fire depends on their size relative to the fire front. At t = 160 s (Figure 5a), the front of the fire is smaller and narrower, and consequently the channels between the groups of trees show some influence on the entrainment patterns, resulting in asymmetrical flow and fire spread patterns. Regions of convergence (Figure 5a,b) suggest that air is being drawn in under a rising plume. This is why convergence lines show up over the flanking edges of the fire, with net wind flow along the flank towards the head fire. Additionally, more focused convergence regions can be seen just downstream of the head fire when it is small. This convergence is occurring downstream of the fire likely because the plume is at an angle leaning downwind and the convergence is occurring underneath the main plume. As the fireline expands and the curvature of the fire front decreases (Figure 5c,d), the fire front is more perpendicular to the wind, and thus more ambient wind can reach the headfire, causing the plume from the head fire to be less focused, and convergence underneath the plume

becomes less pronounced. These complex interactions are highly dynamic and yet tightly coupled, such that unfolding events reflect both local (immediate neighborhood) and persistent upstream effects. Although many of these interactions are brief and transitory, they can play a key role in how fires burn, particularly in heterogeneous fuels such as modeled here. Qualitatively, this figure illustrates that a key role that aggregation may play in modifying fire behavior is through its effects on the wind field.

The complex dynamics of fires burning in heterogeneous fuels are illustrated in Figure 6, which shows fire contours for the medium wind, high canopy cover cases, providing a qualitative comparison of fire geometries at different points in time. To provide a more dynamic view of these contours, two animations are provided, showing progression of these perimeters over time, as supplementary files.

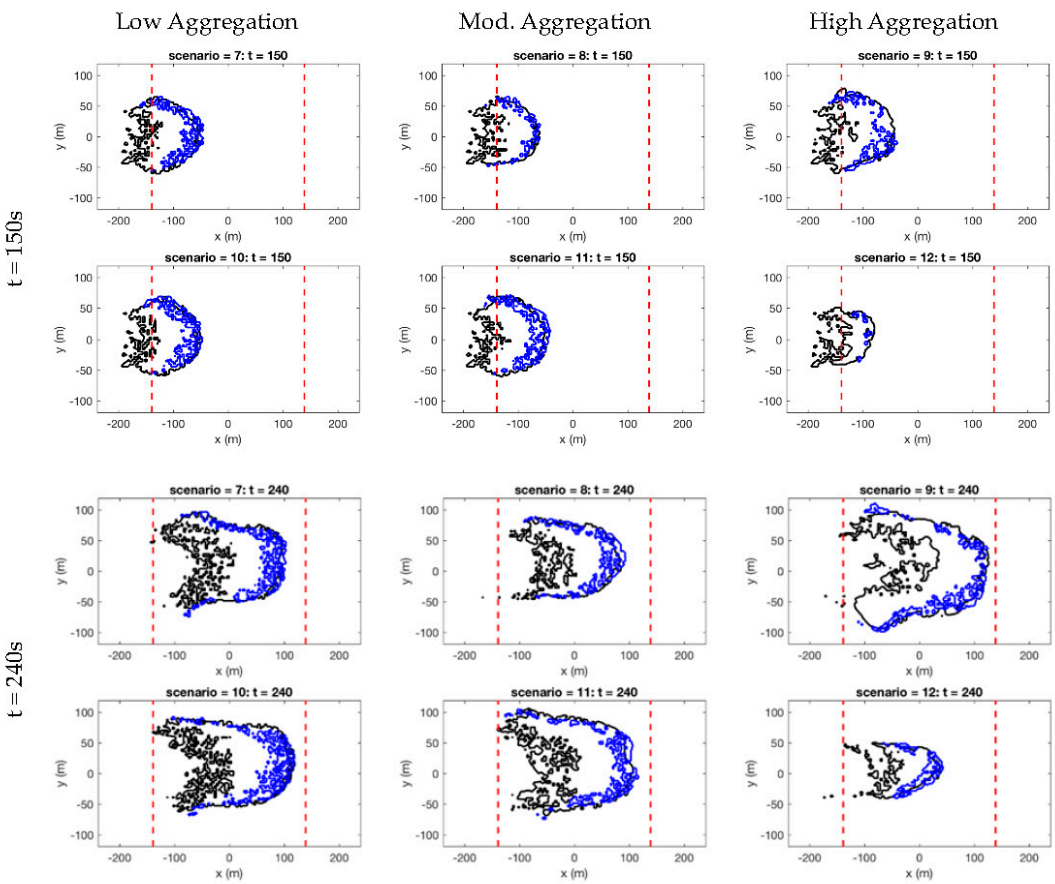

Figure 6. Fire progressions for high canopy cover, medium wind cases, at two points in time, t = 150 s (top two rows) and t = 240 s (bottom two rows). Black lines show contours of active surface fire while blue lines show concurrent contours of active fire in the canopy.

As shown earlier (Figure 4), differences between spatial replicate pairs (upper and lower cases for a given column and point in time) become more pronounced as aggregation scale increases, indicating higher variability in fire behavior. Differences in spread pattern and geometry that started fairly early in the fire progression (at t = 150 s) translate to significant changes as time progresses (t = 240 s). As these cases share identical fuel loads, vertical distributions, and other fuel properties, it seems likely that these persistent disparities in fire behavior must relate to altered dynamics in the wind field arising from differences in spatial pattern.

Time and space averaged vertical profiles of mean wind velocity in the streamwise (x) direction $\overline{U}$ for the same medium wind speed illustrate differences in the wind field arising from effects of spatial aggregation (Figure 7). Differences between replicate pairs (same colors) are hardly perceptible for low aggregation cases, but increase dramatically with aggregation, such that one high aggregation replicate

yields mean velocity values about 40% higher than the second high aggregation replicate (~2.4 m s^{-1} vs. ~1.7 m s^{-1}) at the base of the canopy. Differences in wind velocities extend far above the height of the canopy. As these profiles are spatially averaged over the entire vegetation modification zone, and temporally averaged over the period while the fire burns through that area, they represent significant and lasting (i.e., non-transient) differences, demonstrating that the unique spatial patterns of the fuels are interacting with the wind field in fundamentally different ways.

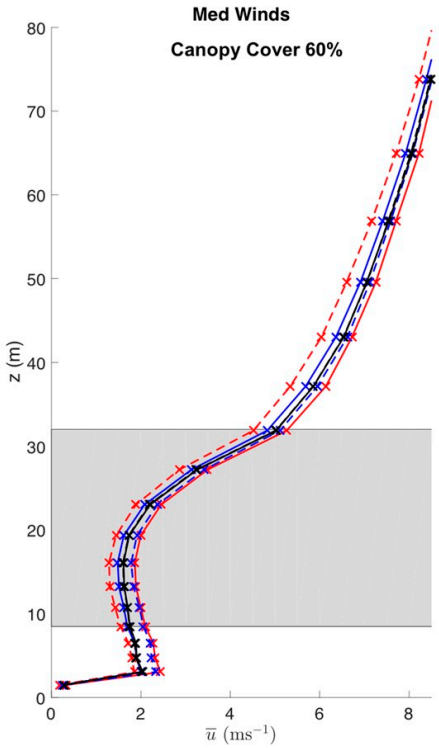

Figure 7. Spatially and temporally averaged vertical profiles characterizing streamwise (forward) wind flow velocity, $\overline{U}$, on the x axis, with increasing height on the y axis. Lines with X's represent 60% cover cases while lines without X's represent 30% cover cases. Red lines show profiles for high aggregation cases, blue lines show moderate aggregation cases and black lines show low aggregation cases. The spread of profile lines of similar colors illustrates differences in winds arising from interactions between fuel spatial patterns, ambient winds, and the fire; differences between replicates are highest for high aggregation cases. The gray area indicates the vertical range within which the canopy is found.

These differences in the wind field are further reflected in the kinematic heat flux, $\overline{W\prime\theta\prime}$ (Figure 8).

Differences between spatial replicate pairs for high aggregation cases are roughly three and ten times higher than the corresponding differences between moderate aggregation and low aggregation cases (Figure 8a); these differences are of similar magnitude to the differences arising between 60% (Figure 8a) and 30% cover with the same wind speed (Figure 8c). Given that the 60% canopy cover cases have exactly twice the canopy fuels as the 30% canopy cover cases, this highlights the potential variability in fire behavior that can arise from aggregated spatial fuel patterns. Overall the highest relative differences arising from spatial aggregation are seen in the medium wind, 60% cover cases (Figure 8a); differences are less pronounced in both the high wind, high cover cases (Figure 8b) and the medium wind, low cover cases (Figure 8c), suggesting a relatively lower effect of unique spatial patterns in higher winds and lower cover (see also Figure 4). These lines of evidence suggest that aggregation significantly affects fire behavior, primarily through increasing variability in outcomes, but that these effects are sensitive to both winds and cover.

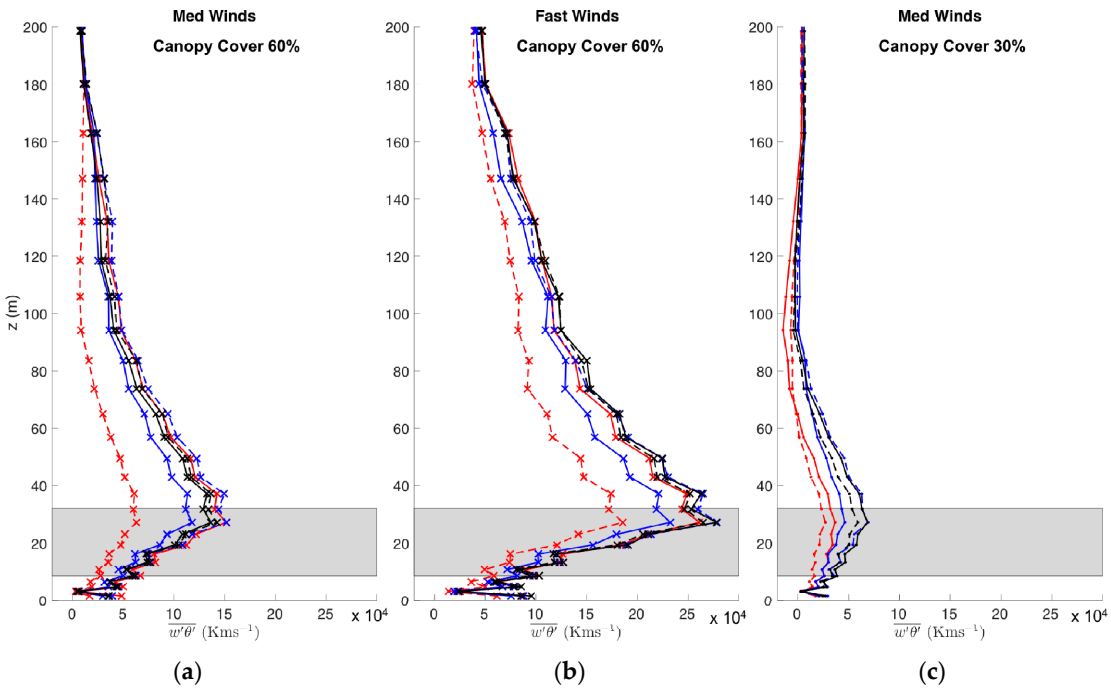

Figure 8. Spatially and temporally averaged vertical profiles characterizing the kinematic heat flux, $\overline{W'\theta'}$, (on the x axis) with increasing height (y axis), for (**a**) 60% canopy cover, medium winds cases, (**b**) 60% canopy cover, fast winds cases, and (**c**) 30% canopy cover, medium winds cases. Red lines show profiles for high aggregation cases, blue lines show moderate aggregation cases, and black lines show low aggregation cases. All three plots share the same x and y axes. The spread between profile line pairs (same color) illustrates differences between spatial replicates. Across all three subplots differences are highest for the high aggregation cases (red lines); differences are most pronounced for medium wind, high canopy cover cases (**a**) fuel spatial patterns; differences between replicates are highest for high aggregation cases.

4. Discussion

Using a physics-based fire behavior model, we carried out a numerical experiment to explore the effects of spatially aggregated fuel patterns on fire behavior, and to examine the sensitivity of those effects to different wind speeds and levels of canopy cover, used here as a simple proxy for canopy fuel load. While most fire models recognize wind speed and fuel load as drivers of fire behavior, the capacity to model and phenomenologically explore interactions between fine-scale canopy spatial heterogeneity, the wind field, and fire behavior is unique to physics-based fire behavior models. Our results, through both quantitative and qualitative analyses, suggest that fine-scale canopy fuel spatial patterns can affect both mean and variability in fire behavior outcomes. Aggregated fuel patterns appear to influence fire behavior first through impacts to the wind field, which can either locally accelerate or decelerate fire spread as ambient winds are channeled through openings or slowed by drag from groups of tree crowns. Fuel spatial patterns additionally influence fire behavior either by enhancing or reducing opportunities for spread through positive or negative feedbacks over time as the fire progresses, as characterized by the kinematic heat flux. Statistical analysis found that spatial aggregation had a significant effect in reducing mean fire front intensity, as well as potentially significant reductions in both kinematic heat flux ($\overline{W'\theta'}$) and forward spread rate in high aggregation cases. However, effects of spatial aggregation on variability in fire behavior, as measured by differences between paired replicates, were more pronounced than effects on mean fire behavior metrics, consistently increasing for all fire behavior metrics with scale of spatial aggregation. This variability was less pronounced in simulations with higher wind speeds and lower canopy cover. Collectively, our results thus suggest

three hypotheses: (1) fine-scale fuel heterogeneity will increase variability in fire behavior, (2) such variability will increase with spatial scale of heterogeneity, and (3) this variability in fire behavior will show greater sensitivity to fuel spatial patterns under less extreme environmental or fuel conditions. Subsequent studies can test our hypotheses with analyses examining shifts in variance and across a broader range of spatial scales.

Our detailed examination of fine-scale fuel heterogeneity and its interactions with fire behavior represents an example of a fine-scale pattern interacting with a fine-scale process. Our study focused on the immediate fire event, at fine spatial scales (meters) and temporal scales (seconds). In the broader context of pattern and process interactions in such forests, the immediate fire event is a fleeting moment, but the footprint of such events extends much farther in time. A comprehensive examination of how the immediate fire event influences subsequent patterns and processes requires modeling of processes well beyond the scope of this paper (i.e., fire effects, stand dynamics, and seedling establishment). There is a need for improved understanding of the linkages between fire behavior and fire effects, and more broadly, between physical and biological processes, over time [79]. Recent systems have been developed which show some promise in this arena [67]. While the perspective offered by the present study regarding interactions of pattern and process is limited by its emphasis on the fire event itself, the fire simulations we carried out have potential implications for management and for ecological understanding.

Our cases share some structural similarities with real world dry, fire-frequent forests both past and present. Historically, dry fire-frequent forests typically had lower canopy cover, similar to our 30% canopy cover cases. Conversely, in many cases such forests, now with disturbed or altered fire regimes, are similar to our 60% canopy cover cases. Our moderate aggregation cases are similar in character to patterns observed in intact fire-frequent regimes, with mosaics of individual trees, clumps and openings on a scale of <0.4 ha, while our high aggregation cases, with mosaics of openings and clumps mostly larger than 0.4 ha, may be more representative of forests characterized by a more mixed severity fire regime [14]. In contrast, our low aggregation cases, in which the level of aggregation was no more than random, are probably fairly comparable to some contemporary forests with more homogeneous conditions, either as a result of regularly spaced thinning treatments (for 30% canopy cover cases) or as a result of fire suppression or other land use practices (for 60% canopy cover cases). The broad reduction in fire behavior between our 60% and 30% canopy cover cases, regardless of aggregation pattern, agrees with a number of other studies that demonstrate reduction in fire behavior as a result of fuel treatments [36], including a recent physics-based fire modeling study in similar fuels [63], and reinforces the idea presented in that paper that fuel treatments with aggregated patterns are likely similar to more conventional treatment approaches in reducing fire behavior. Our study showed sensitivity to wind speed, suggesting that fuel treatments are likely limited in their effectiveness under more severe conditions. This decreased effectiveness under more severe conditions has been proposed at landscape scales as well [44].

Our findings that aggregated fuel patterns increase variability in fire behavior reinforce contemporary understanding in fire ecology. If heterogeneity in fire behavior translates to heterogeneous fire effects, as seems likely from some detailed studies [80,81], then aggregated fuel patterns should lead to greater diversity in subsequent regeneration and growth patterns, a critical aspect of forest resilience [14,79]. Additionally, our hypothesis of increased sensitivity to aggregated fuel patterns under less severe conditions, if correct, bolsters the idea that greater fine-scale heterogeneity in fire behavior should result with lower wind speeds or less active surface fuels. Under such conditions, in many cases, fire behavior should exhibit binary behaviors, where fires either burn, or burn out. The arena of conditions at the lower end of fire behavior is also important to explore as it has important implications for seedling survival and local habitat refugia for different species; survival of small patches of regeneration as well as coherent areas of mineral soil are attributed to be important mechanisms in the formation of structurally diverse stands [14]. More work is needed to

fully understand the range of conditions, and spatial scales at which different sources of fuel spatial heterogeneity may affect fire behavior.

Both fire and fuels are complex in nature, so studies exploring the intersection of fire and fuels face challenges in navigating variability from a large number of sources. As an exploratory study with a goal of generating new hypotheses, we chose to simplify our representation of certain aspects of forest fuels to eliminate some sources of variability and isolate others. In so doing, we were able to focus on the effects of horizontal spatial aggregation patterns, modeling vertical fuel structure as a distribution. Our statistical modeling approach to generate aggregated fuel patterns offered the benefit of replicability but with the cost of significant abstraction of real forest structure. Consequently, our stochastically generated fuel patterns lack fine-scale heterogeneity in surface fuels, individual tree size and shape and between-tree variability, as well as a more complex vertical structural diversity found in most real forests. Similarly, for the sake of simplicity, we modeled all trees identically to isolate the effects of within-stand horizontal distribution canopy fuel patterns. In reality, variability in several key canopy fuel properties, both within and between individual trees, as well as between species, probably plays an important role in how patchy/clumpy fuel distributions respond to and influence fire. Finer scale investigations suggest that tree architecture and fuel distribution within a tree crown can significantly impact how individual trees burn [60,66,82]. It is likely that variability in fine-scale fuel properties, chemical composition [83] and size class all play key roles in how trees burn and how fire propagates.

While future modeling experiments and field studies should be carried out to explore the effects of these different sources of heterogeneity systematically, we suggest that incorporation of these additional sources of variability could have different outcomes, depending on the situation. The majority of these additional sources of variability are spatially fine scale in nature, such as differences between trees or adjacent surface fuel cells. Thus, in the absence of a larger scale source of heterogeneity, such as wide differences in fuel moisture or fuel load across the stand, inclusion of these additional sources of heterogeneity would most likely result in a higher degree of variability at fine scales but a lower degree of variability overall; we would hypothesize that fine scale heterogeneity should "wash out" over relatively short length scales. If this were the case, the capacity of the system to absorb local high variability may enforce broader-scale homogeneity. This pattern and process interaction could be part of the extraordinary resilience in such dry, fire-frequent forests in the past.

Finally, while the detailed simulations carried out here focused on fires burning in a relatively small area (~18 ha), insights gained regarding spatial heterogeneity may be relevant at landscape scales. Understanding that spatial patterns can induce variability in disturbances like fire suggests that developing better methods to characterize variability in forest cover and spatial pattern would be useful for landscape management. At present, finer scale variability is not represented or considered in many landscape scale-mapping efforts. Capturing and retaining this information, through improved remote sensing, spatial analysis and modeling approaches, could strengthen management decisions in many areas, ranging from better characterizations of uncertainty in fire behavior to improved assessments of habitat quality or other ecological values of interest. As landscapes in many parts of the world are experiencing rapid changes through shifts in land use and from climate change, improved characterization of uncertainty will become increasingly important.

5. Conclusions

We carried out an exploratory series of numerical experiments examining the effect of heterogeneous fuel patterns on fire behavior and the sensitivity of those effects to canopy cover and wind speeds. Qualitative and quantitative approaches suggest that spatial fuel patterns can significantly affect fire behavior. However, while our study achieved the objective of exploring this complex arena and suggesting new hypotheses, more work is needed. Subsequent work, with a larger number of replicates, should be carried out to more robustly characterize the magnitudes of uncertainty in different fire behavior metrics that can arise from both spatial fuel heterogeneity and other factors.

In recent years a number of new tools and approaches have been developed which facilitate this type of analysis e.g., [84,85]. Use of such tools, and continuing work, will help to precisely identify the key mechanisms and consequences of fuel spatial patterns on fire behavior. Our study illustrates that the depth and breadth of quantitative data provided by physics-based models such as FIRETEC have a unique place in building that knowledge. However, well documented and quantitatively measured experiments in the field, at laboratory, and even bench scales are critical to ensuring hypotheses or contributions from less expensive and less logistically constrained numerical studies can always be vetted by real world data. The complexities of interactions and physical processes involved in fire spread require coordinated efforts and collaborative work between experimentalists and modelers across all scales to achieve full understanding of wildland fire.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-445X/6/2/42s1; Video S1: fire_perimeters_animation_medium_winds.wmv; Video S2: fire_perimeters_animation_fast_winds.wmv.

Acknowledgments: This work was made possible by funding from the Joint Fire Science Program of the US Department of Agriculture (USDA) and US Department of the Interior (USDI), Project # 12-1-03-30 (STANDFIRE), as well as from USDA Forest Service Research (both Rocky Mountain Research Station and Washington office) National Fire Plan Dollars, through Interagency Agreements 13-IA-11221633-103 with Los Alamos National Laboratory, and Research Joint Venture Agreement 11-JV-11221633-207 with Colorado State University. Los Alamos National Laboratory's Institutional Computing Program provided the essential computational resources to complete this project.

Author Contributions: R.A.P., R.R.L, J.W. and J.S. conceived and designed the experiments; J.W. and R.R.L. performed the experiments; R.A.P., F.P., C.H., J.S., R.R.L. and J.W. analyzed the data and produced figures/animations; and R.A.P. wrote the paper, with contributions from all co-authors.

Conflicts of Interest: The authors declare no conflict of interest. The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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