Progress in Understanding Bark Beetle Effects on Fire Behavior Using Physics-Based Models

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1. Introduction

Bark beetle outbreaks are a major disturbance of forests throughout western North America affecting ecological processes and social and economic values (Amman 1977, Bond and Keeley 2005). Since the 1990s, bark beetle outbreaks have affected between 1.1 and 13.5 million acres in the western United States and an additional 13.5 million acres in British Columbia (Meddens et al. 2012). Tree mortality resulting from bark beetles has affected lodgepole pine, ponderosa pine, spruce-fir, Douglas-fir and pinyon pine forest types (Figure 1). The extent of the recent tree mortality due to bark beetle outbreaks has led to increased scientific, management and public interest in the implications of bark beetle-caused tree mortality for the behavior of subsequent wildfires.

Successful bark beetle attacks result in the disruption of tree physiological function, eventually leading to loss of moisture from the canopy foliage and a change in needle color from green to red (Figure 2). This "red phase" can last for 1 to 4 years, depending on tree species and environmental conditions. Over time the needles begin to drop to the ground, eventually resulting in the complete loss of canopy foliage. This second phase, which may last up to a decade after the bark beetle attack, is often referred to as the "gray phase." Ultimately the dead branches and trees fall to the ground and the "old phase" can persist for decades following bark beetle-caused mortality. Changes in the fuels complex following bark beetle-caused mortality have been characterized for lodgepole pine and spruce-fir dominated forests (Page and Jenkins 2007a, Page and Jenkins 2007b, Jenkins et al. 2008, Derose and Long 2009, Klutsch et al. 2011, Schoennagel et al. 2012, Simard et al. 2011), pinyon-juniper woodlands (Clifford et al. 2008), ponderosa pine forests (Hoffman et al. 2012a) and Douglas-fir forests (Donato et al. 2013).

In general, compared to pre-outbreak green phase forests, bark beetle-affected forests in the red phase are expected to be at higher risk for the transition of surface fires into the canopy, followed by the spread of fires through the canopy. This heightened risk of crown fire is expected to decrease during the gray phase (Jenkins et al. 2008, Hicke et al. 2012).

Figure 1: Landscape-scale bark beetle-caused mortality in ponderosa pine on the Prescott National Forest, AZ (top image; courtesy of Joel McMillin, USDA Forest Service Region 3 Forest Health and Protection), ponderosa pine/mixed conifer forests on the Arapaho-Roosevelt National Forest, CO (middle image; courtesy of Chad Hoffman and LightHawk), and lodgepole pine and spruce-fir forests on the Deschutes National Forest, OR (bottom image; courtesy of Chad Hoffman).

There is disagreement between studies, however, over the direction and magnitude of the effect of bark beetle mortality on potential fire behavior, particularly during the red phase (e.g. Simard et al. 2011). In addition, there are several gaps in our current knowledge that must be overcome in order to develop a generalizable framework that describes the effect of bark beetle mortality on potential fire behavior (Hicke et al. 2012).

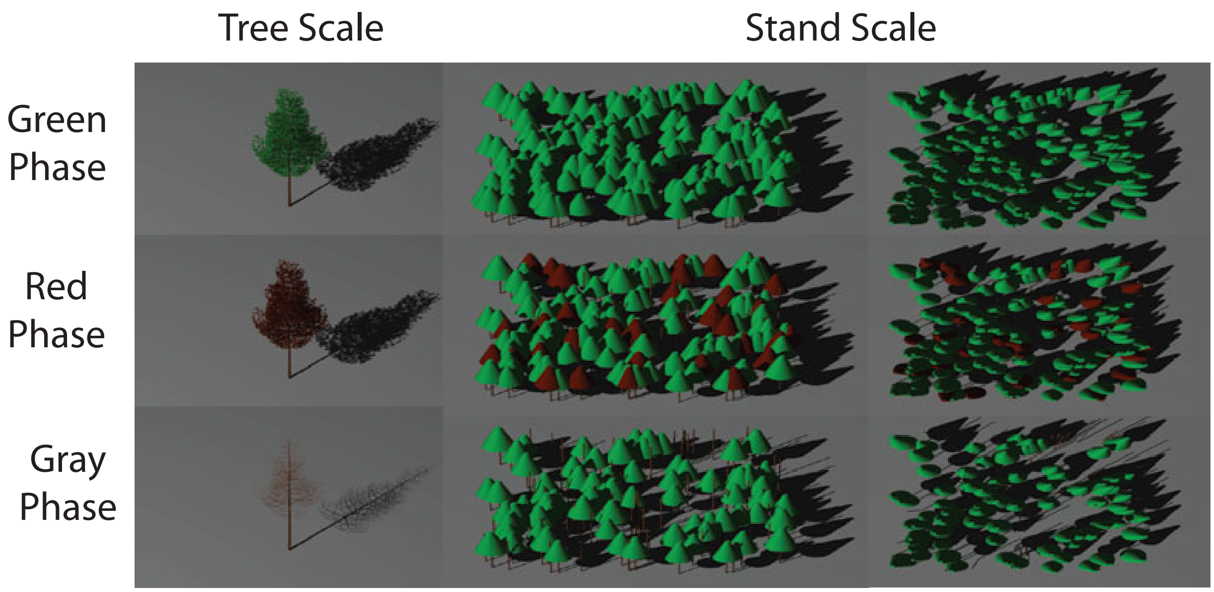


Figure 2. Representation of temporal phases following bark beetle-caused tree mortality at the individual tree and stand scales. These images were developed with the FUEL3D fuel simulation model.

Scientists have identified three ways in which bark beetles can affect fire behavior: 1) changes in the state, amount, and distribution of surface and canopy fuels; 2) changes in fuel moisture and chemical composition; and 3) alterations in micro-climatic influences on fire behavior such as wind velocity, direction and turbulence within stands. In this technical note, we describe the development and application of physics-based computer models for characterizing these effects and evaluating their interactions. Our purpose is to better familiarize fire and land managers with physics-based fire behavior models, and to illustrate their potential uses and benefits in addressing fire behavior in rapidly changing forest environments affected by bark beetle outbreaks. A key aspect of making these models more useful to managers is helping managers better understand the types of questions that they can pose for study with these tools, thus guiding researchers to the most relevant problems.

2. Why physics-based fire behavior modeling?

Due to the risks and difficulties in measuring fuel characteristics, environmental conditions, and fire behavior in bark beetle-affected stands before and during a fire, most studies have used simulation models to explore how changes to fuel complexes as a result of beetle attacks might influence the behavior of subsequent wildfires (Hicke et al. 2012, Jenkins et al. 2012). However, operational fire behavior modeling systems commonly used in the U.S. cannot fully account for the spatial patterns of the fuels or all of the interactions between the fuels, environmental conditions, and the fire. These simplifications in commonly applied operational models have historically been for the sake of simplifying model development, reducing complexity of input parameters, or reducing computational costs. These drivers precluded the solution of complex equation sets based on the assumption that fuels, winds, and environmental conditions (such as topography) are constants, as formulated by Rothermel (1972, 1991) for surface and crown fire rates-of-spread, and Van Wagner (1977) for crown fire ignition and spread criteria.

Such assumptions are particularly questionable in bark beetle-affected areas typically characterized by a complex mixture of dead and live canopy fuels. Further, Cruz and Alexander (2010) suggested that predictions based on the linkages between Rothermel (1972, 1991) and Van Wagner (1977) equations tend to under-predict crown fire hazard. Thus, operational fire behavior modeling systems are significantly limited in their ability to address current knowledge gaps, such as the effect of various levels and rates of beetle-induced mortality on the fire environment and associated potential fire behavior.

Recently developed physics-based fire behavior models such as HIGRAD/FIRETEC (Linn 1997) and the Wildland-Urban Interface Fire Dynamics Simulator (WFDS, Mell et al. 2009) provide alternative modeling frameworks that account for, to some approximation, the major physical processes that influence fire behavior. These models enable approximation of the three-dimensional spatial structure of the fuels complex, as well as the interaction between the fuels complex, wind flow and the fire over space and time. This approach allows the constantly changing, interactive relationship between the fire, the environment, and fuels to be simulated with coupled fire-atmosphere dynamics. FIRETEC and WFDS were developed as research tools and require considerable computational resources and computer simulation time. These models can have substantial input data requirements to describe fuels complexes in three dimensions, and require users to have a working knowledge of fluid dynamics, thermodynamics, combustion and heat transfer.

Both WFDS and FIRETEC have received varying levels of model validation and evaluation. Recent studies include comparisons to measured wind flow through forest stands (Pimont et al. 2009, Mueller 2012), experimental prescribed fires (Linn et al. 2005, Linn and Cunningham 2005, Mell et al. 2007, Linn et al. 2012), and experimental laboratory fires (Mell et al. 2009, Castle et al., 2013). In addition, a considerable number of validation studies have been completed for FDS (Fire Dynamics Simulator), the parent model of WFDS (McGrattan et al. 2010), for fire protection engineering applications.

Although physics-based models have not received full validation across a wide range of observed fire behavior and environmental conditions, especially in bark beetle-affected areas, they can produce realistic fire behavior (Linn et al. 2013). However, it is important to remember that physics-based models still require a number of simplifications of a very complex reality, and should be interpreted and used with caution. Efforts to further validate both WFDS and FIRETEC using field and laboratory data sets are ongoing.

3. What we are learning from physics-based models:

3.1 Level of tree mortality affects potential fire behavior

Using fuels data from 11 locations in central Oregon and Idaho to populate WFDS, Hoffman et al. (2012b, 2013) examined how the level of mountain pine beetle-induced lodgepole pine mortality influenced potential fire behavior during the red phase. All simulations were conducted under moderate conditions where the wind speed averaged 4.5 mph at 20 ft above the ground, and the surface fire spread and intensity were 19.8 ft min^{-1} (0.1 m s^{-1}) and 72 btu ft^{-1} s^{-1} (250 kW m^{-1}), respectively. Using the same 11 lodgepole pine stands and wind velocities, Hoffman et al. (2013) investigated the relationship between the level of bark beetle-caused mortality and potential fire behavior for three different levels of surface fire intensity (36, 72, and 144 btu ft^{-1} s^{-1} or 125, 250 and 500 kW m^{-1}) across five levels of bark beetle-caused mortality (0, 25, 55, 75, 100%). The fireline intensities simulated by Hoffman et al. (2012b, 2013) represent surface fires that could be suppressed by fire resources with hand tools for the low intensity simulations, while the moderate and high intensity simulations represent fires that could not be suppressed with hand tools.

Hoffman et al. (2012b) found that the simulated amount of canopy fuel consumption and the crown fire intensity were both positively related to the level of lodgepole pine mortality during the red phase, and that the predicted consumption and intensity at all levels of mortality above 10% were significantly different than the pre-outbreak scenarios (Figure 3). However, while both canopy fuel consumption and crown fire intensity tended to increase as the level of tree mortality increased during the red phase, Hoffman et al. (2013) found that the slope of the relationship was dependent upon the surface fire intensity.

Taken together, the results from Hoffman et al. (2012b, 2013) suggest that crown fire intensity and canopy fuel consumption both increase during the red phase. However, the magnitude of these increases depends on the level of tree mortality and the surface fire intensity; changes in fire behavior between pre-outbreak and red-phase fuels were most pronounced when surface fire intensities were simulated with moderate and low surface fire intensities (Hoffman et al. 2013). At high surface fire intensities, mortality level had little effect on subsequent crown fire behavior because the relative differences between crown fires with and without beetle kill were fairly subtle.

Hoffman et al. (2013) suggested that bark beetles have a larger effect on subsequent fire behavior during the red phase when the pre-outbreak surface fire intensity is not large enough to result in crown ignition in the pre-outbreak stand. They further suggested that fire behavior during the red phase may not always show increased canopy fuel consumption or crown fire intensity compared to a fire under the same conditions in the pre-outbreak forest.

The findings of Hoffman et al. (2012b, 2013) agree with other theoretical relationships based on simulation modeling (Jenkins et al. 2008, Hicke et al. 2012), as well as with laboratory-scale studies, which indicate that reduced foliar (needle) moisture content increases flammability (Xanthopoulos and Wakimoto 1993, Dimitrakopoulos and Papaioannou 2001, Liodakis and Kakardakis 2008, Babrauskas 2008, Jolly et al. 2012). Although there is limited quantitative data from actual forest fires burning in lodgepole pine forests during the red phase, an increase in crown fire activity particularly under moderate burning conditions has been observed in recent years (Wildland Fire Lessons Learned Center 2012).

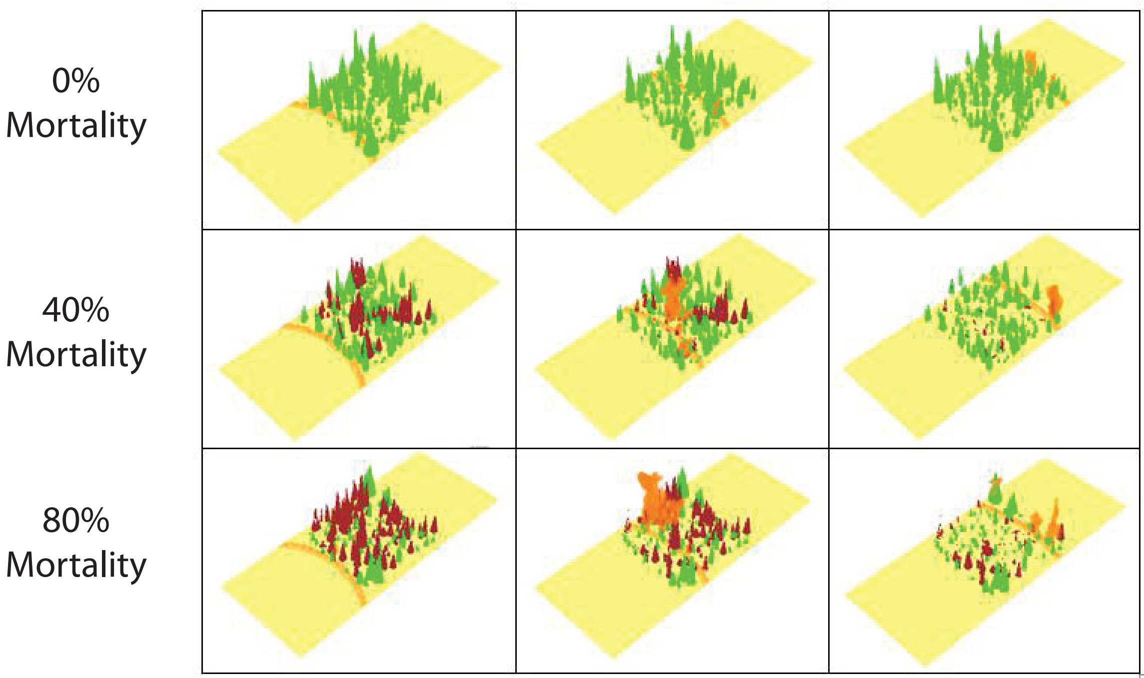


Figure 3. WFDS simulations through time for 0%, 40% and 80% mortality during the red phase in a lodgepole pine-dominated forest under moderate environmental conditions. Time proceeds from left to right in all three cases. Simulations show a clear increase in crown fire activity and total fuel consumption as the level of mortality increases.

3.2 Bark beetle-caused tree mortality influences on wind flow and potential fire behavior

Linn et al. (2013) used HIGRAD/FIRETEC to explore the effects of bark beetle-caused tree mortality on within-stand wind flow patterns and the associated fire behavior in pinyon-juniper woodlands of the southwestern United States. Using fuels data collected in the field, they simulated the wind flow and fire behavior for pre-outbreak (no mortality) as well as red and gray attack phases with two different open wind speeds that were used to represent moderate conditions. Their stand was simulated to represent an area with high pre-outbreak tree density (405 trees per acre) and high levels of pinyon tree mortality from bark beetles (77% of the trees in the stand).

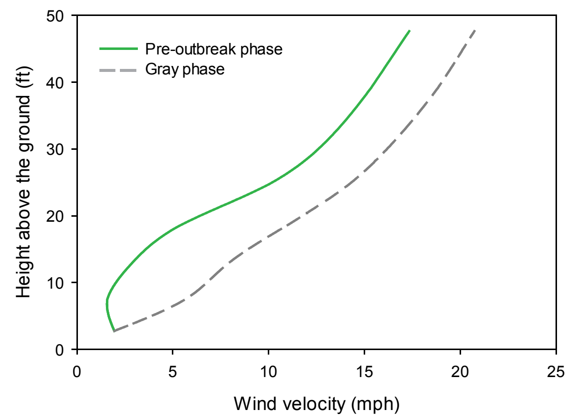


Figure 4. Changes in simulated wind flow for the pre-outbreak (green phase) and the gray phase for the high wind speed scenarios in pinyon-juniper woodlands, adapted from Linn et al. (2013).

The loss of pinyon needles in the tree canopies during the gray phase resulted in an increase in the within-canopy wind flow and turbulence, and altered vertical wind flow profiles (Figure 4). Because Linn et al. (2013) simulated the red phase as one in which all needles of dead trees remained in the overstory canopy, there were no differences in wind fields between the pre-outbreak and red phases.

In addition to changes in the wind flow, Linn et al. (2013) also found that the predicted fire rates-of-spread were between 1.8 and 2.6 times faster during the red phase as compared to the pre-outbreak green phase (Figure 5).

The gray phase simulations also showed increased rates-of-spread and heat release rate compared to the pre-outbreak scenario. However, as Linn et al. (2013) point out, the raw simulations combine the effects of both the altered wind flow and altered fuels complex. Further analysis suggested that the rates-of-spread were 13.5 percent less during the gray phase as compared to the pre-outbreak simulations when the effect of altered within-canopy wind velocity was considered. Thus, Linn et al. (2013) suggested that changes in wind flow may have a larger effect on fire rate-of-spread than the altered fuels during the gray phase, at least for pinyon-juniper woodlands.

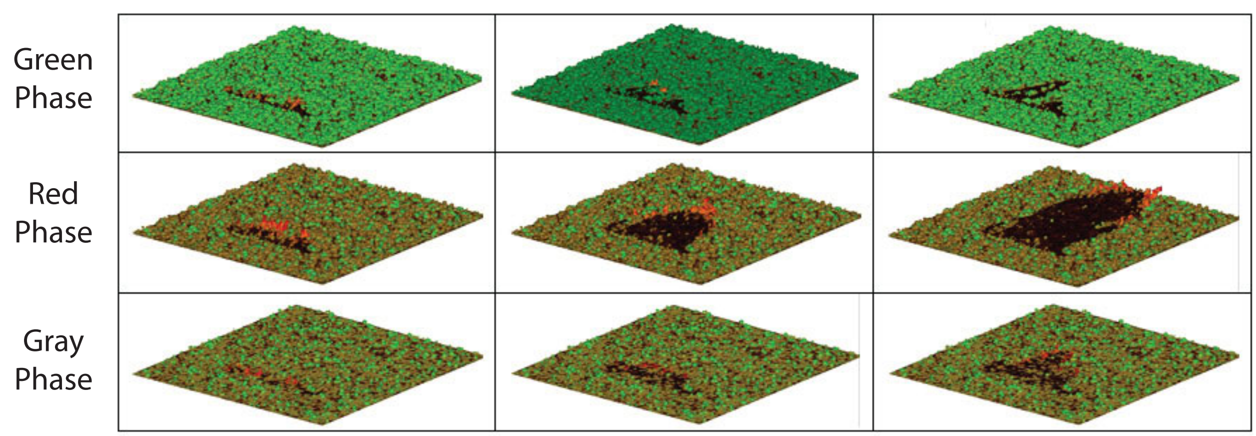


Figure 5. FIRETEC simulations from Linn et al. (2013) showing the fire perimeter and fuel consumption through time for the green, red and gray phases with a 27 mph 20 ft open wind for a pinyon-juniper woodland impacted by a pinyon Ips bark beetle outbreak. Time proceeds from left to right in all three cases.

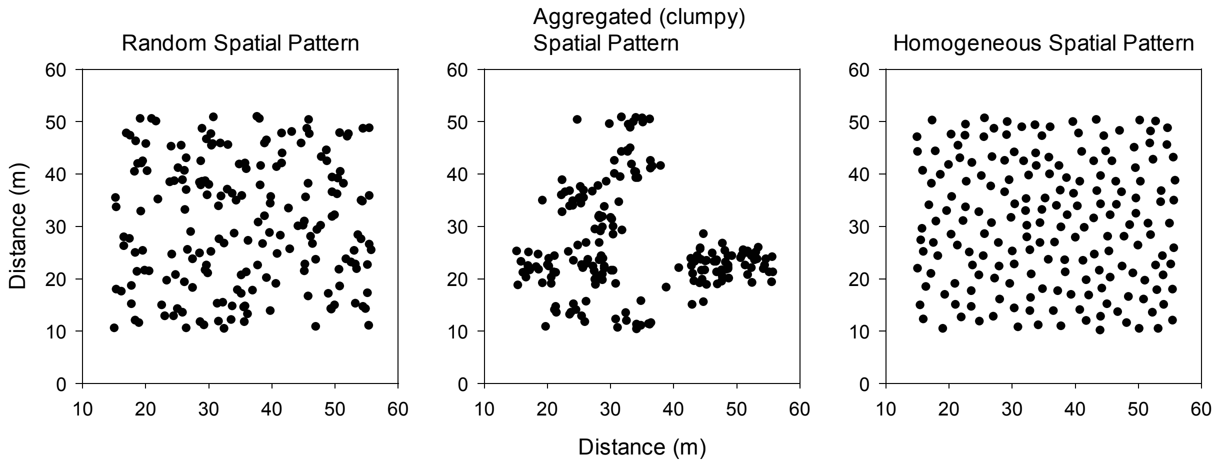


Figure 6. Example simulated spatial point patterns from Hoffman et al. (2012b and 2013) for a lodgepole pine-dominated stand with 404 trees per acre.

Based on their simulation results, Linn et al. (2013) suggested that in sparse, heterogeneous fuels such as those found in the pinyon-juniper woodlands, bark beetle-caused tree mortality affects fire rate-of-spread by decreasing the canopy needle moisture content during the red phase, and increasing within-canopy and above-canopy wind speeds during the gray phase. Although there are few data from actual fires in bark beetle-affected areas for comparison, the increases in rates-of-spread found by Linn et al. (2013) during the red phase do compare well with values estimated by Alexander and Cruz (2013), who suggested an increase in the rate-of-spread of between 2.5 and 3.6 times the pre-outbreak scenario.

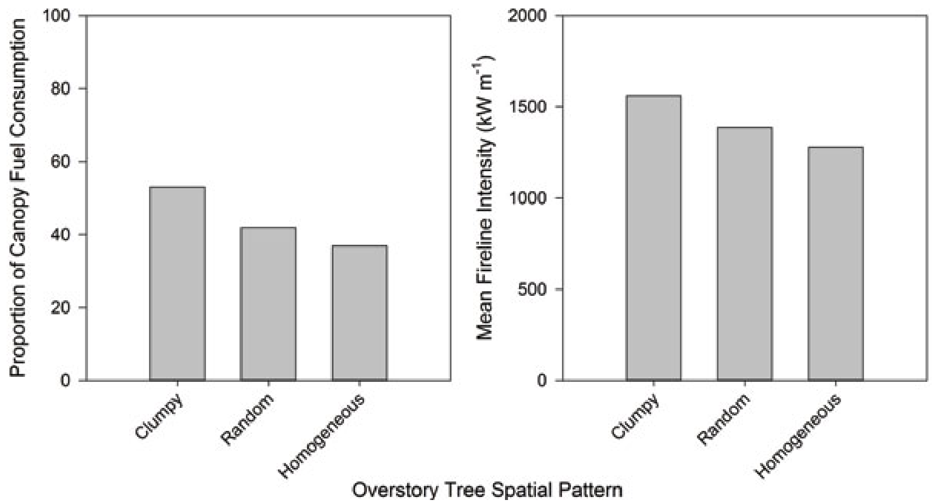
3.3 Tree spatial patterns influence potential fire behavior in bark beetle-affected stands

In addition to evaluating the potential effects of various levels of mortality, the effects of various overstory tree spatial patterns, and thus various mortality patterns, can also be investigated. Hoffman et al. (2012b) simulated fire behavior in lodgepole pine-dominated forested stands using WFDS with several different spatial arrangements of trees (Figure 6) . These simulations were conducted using the same stand level data from central Oregon and Idaho and were simulated using the same moderate surface fire and wind flow conditions as reported in Hoffman et al. (2012b).

Investigations concerning the roles of spatial complexity on fire-fuel-atmosphere interactions and resulting fire behavior are not possible with current operational tools because they are not designed to account for heterogeneous spatial density of trees, or the significant effect that spatial tree arrangement has on the winds that penetrate the canopy and push the winds. By changing the tree arrangement, the local crown continuity is changed as well as the winds that push both ground and crown fires (Pimont et al. 2009, 2011). The physics-based models that couple fire-atmosphere dynamics provide the ability to examine the sensitivity of these heterogeneous effects of tree spacing and mortality arrangement, thus providing insight for managers and the development of future operational tools.

During the red phase in the Hoffman et al. (2012b) study, simulations show that canopy fuel consumption and crown fire intensity were between 10 and 16% greater for aggregated or clumpy tree arrangements compared to random and homogeneous arrangements (Figure 7). These results suggest that the spatial pattern of overstory trees can also influence the effect of bark beetle caused-tree mortality on fire behavior. However, further studies that investigate the interactions between tree spatial patterns, within-canopy wind flow and fire behavior are needed.

Figure 7. Influence of overstory tree spatial pattern on the proportion of canopy fuel consumption and the mean fireline intensity from WFDS simulations in lodgepole pine-dominated forests (Hoffman et al. 2012b).



Although there are no investigations of the role of spatial pattern on potential fire behavior during the gray phase, Linn et al. (2013) suggested that the effect of altered canopy fuels on within-canopy wind flow may be a driving factor in determining fire behavior during the gray phase. While research investigating the effect of spatial pattern on fire behavior is in its infancy, several other recent modeling studies have also shown that there are complex interactions between spatial pattern, wind flow, and fire behavior (Parsons 2007, Pimont et al. 2011, Linn et al. 2013). Additional research and simulations are needed to better understand the potential influence of tree spatial pattern and fuel heterogeneity on fire behavior.

4. Conclusions

Physics-based fire behavior models are useful for exploring the potential ways that a mosaic of live and dead fuels resulting from bark beetle-induced tree mortality influences coupled fire-atmospheric interactions, and the resulting potential fire behavior. Both WFDS and FIRETEC have undergone some level of validation and evaluation; however, no systematic comparison has been conducted between the results of either physics- or operational-based fire behavior models with experiments or observations from fires burning in areas that have been impacted by bark beetles.

Nonetheless, the results from models such as WFDS and FIRETEC can be reasonably used to suggest possible ways that interactions between physical phenomena across various fuels complexes and environmental conditions influence potential fire behavior (Linn et al. 2013). Results from the application of physics-based models involving bark beetle-caused tree mortality suggest the following:

1) The potential fire behavior in post-outbreak beetle affected forests is sensitive to the level of tree mortality and the spatial pattern of the dead trees.

2) The effect of bark beetle-caused tree mortality on subsequent fire behavior during the red phase, when dead needles cling to the trees, varies with surface fire intensity. The largest influence of bark beetle-caused tree mortality may occur under moderate burning conditions that result in surface fire intensities that are just below the threshold for crown fire ignition in pre-outbreak forests.

3) The reduction in canopy biomass associated with the gray phase, when dead needles have fallen to the ground, can result in greater wind penetration into the canopies, thus increasing within-canopy wind speed and turbulence. These changes can cause an increased fire rate-of-spread in gray phase stands compared to pre-outbreak fire behavior, especially in patchy, mixed-fuel forest types such as pinyon-juniper woodlands.

4) Increases in fire behavior (such as rate-of-spread, fireline intensity and fuel consumption) can occur in both the red and gray phases relative to pre-outbreak conditions, depending upon the level of tree mortality, the wind speed, and the surface fireline intensity generated by the combustion of the surface fuels.

Although physics-based models have been useful for further exploring the potential interactions between bark beetle-influenced fuels complexes, atmospheric processes and potential fire behavior, many key gaps remain in our understanding of beetle and fire interactions (Hicke et al. 2012). Fire behavior modeling systems will likely remain an important aspect of future research investigating bark beetle-fire interactions, but there is a need for further case-study evaluation, and for well-quantified operational and experimental fires in bark beetle-affected forests. Data from additional case studies and operational and experimental fires could provide a means of validating hypotheses generated from simulation experiments such as the ones highlighted here. Case studies could also improve our understanding of the conditions under which various fire behavior models do and do not perform well, which would help with further development of new empirical and physical models.

Given that physics-based models were designed as research tools, have large input data requirements and computational costs, and require specialized expertise to conduct simulations, it is unlikely that they will replace operational models which are designed to run faster than real time and require minimal inputs. However, physics-based models can assist managers by offering insights into how and why bark beetle-caused tree mortality affects forest fire behavior in ways that operational models do not. For example, these models can provide insights into how fires might behave under fluctuating winds compared to steady conditions, or in mixtures of varying fuel moistures compared to average conditions, or in areas with clumpy tree mortality and complex topography. Untapped opportunities exist for collaboration between physics-based fire scientists and managers to field-test models and advance scientific and practical understanding of fires in forests with many bark beetle-killed trees.

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About the Colorado Forest Restoration Institute

The Colorado Forest Restoration Institute (CFRI) was established in 2005 as an application-oriented program of the Department of Forest & Rangeland Stewardship in the Warner College of Natural Resources at Colorado State University. CFRI's purpose is to develop, synthesize, and apply locally-relevant science-based knowledge to achieve forest restoration and wildfire hazard reduction goals in Colorado and the Interior West. We do this through collaborative partnerships involving researchers, forest land managers, interested and affected stakeholders, and communities. Authorized by Congress through the Southwest Forest Health and Wildfire Prevention Act of 2004, CFRI is one of three Institutes comprising the Southwest Ecological Restoration Institutes, along with centers at Northern Arizona University and New Mexico Highlands University.

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