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Modeling spatial and temporal dynamics of wind flow and potential fire behavior following a mountain pine beetle outbreak in a lodgepole pine forest

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ABSTRACT

Patches of live, dead, and dying trees resulting from bark beetle-caused mortality alter spatial and temporal variability in the canopy and surface fuel complex through changes in the foliar moisture content of attacked trees and through the redistribution of canopy fuels. The resulting heterogeneous fuels complexes alter within-canopy wind flow, wind fluctuations, and rate of fire spread. However, there is currently little information about the potential influence of different rates and patterns of mortality on wind flow and fire behavior following bark beetle outbreaks. In this study, we contrasted within-canopy wind flow and fire rate-of-spread (ROS) at two different ambient wind speeds using FIRETEC for two differing bark beetle attack trajectories for a lodgepole pine (*Pinus contorta*) forest. These two attack trajectories represent different realizations of a bark beetle outbreak and result in different amounts and patterns of mortality through time. Our simulations suggested that the mean within-canopy wind velocities increased through time following the progression of mortality. In addition, we found that for a given level of mortality, a bark beetle outbreak that resulted in a higher degree of aggregation of canopy fuels had greater mean within-canopy wind velocities due to the channeling of wind flow. These findings suggest that bark beetle mortality can influence the mean within-canopy wind flow in two ways: first, by reducing the amount of vegetation present in the canopy acting as a source of drag; and second, by altering spatial patterns of vegetation that can lead to channeling of wind flow. Changes in the fire rate-of-spread were positively related to the level and continuity of bark beetle mortality. Peak rates of spread were between 1.2 and 2.7 times greater than the pre-outbreak scenario and coincided with a high level of mortality and minimal loss of canopy fuels. Following the loss of canopy fuels the rate of fire spread declined to levels below the initial phases of the outbreak in low wind speed cases but remained above pre-outbreak levels in high wind speed cases. These findings suggest that the rate and pattern of mortality arising from a bark beetle outbreak exerts significant influence on the magnitude and timing of alterations to the within-canopy wind flow and rate of fire spread. Our findings help clarify existing knowledge gaps related to the effect of bark beetle outbreaks on fire behavior and could explain potential differences in the reported effects of bark beetle outbreaks on fire behavior through time.

1. Introduction

Native bark beetles (Coleoptera: Curculionidae, Scolytinae) are important disturbance agents of forests throughout North America. The mortality of trees during a bark beetle outbreak results in spatial alterations to forest structure, the fuels complex, and a variety of ecological processes across a wide range of temporal and spatial

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scales (Raffa et al., 2008). The collective influence of individual tree mortality affects the number as well as the size and age class distribution of living trees (Raffa et al., 2008). Changes in the structure of forest canopies through time result in altered gradients of foliar moisture contents and vertical and horizontal spatial arrangement of biomass that in turn influence the micro-climatic conditions within the stand. Altered stand structure, composition, and microclimate following bark beetle outbreaks can persist for tens of decades, thus, creating distinctive fuel and environmental conditions for wildfires through time. The recent extent of large-scale bark beetle-caused tree mortality across western North America has resulted in increased concern about the potential effect of bark beetle outbreaks on altered fuels complexes, the associated fire environment especially wind speeds and the potential fire behavior (Jenkins et al., 2008, 2012).

Although it has long been recognized that bark beetle-caused tree mortality may influence the fuels complex and subsequent fire behavior (Brown, 1975), only recently has the research community focused on quantifying such effects (Page and Jenkins, 2007; DeRose and Long, 2009; Klutsch et al., 2011; Simard et al., 2011; Hoffman et al., 2012a,b, 2013; Schoennagel et al., 2012; Donato et al., 2013; Linn et al., 2013). Individual attacked trees pass through an observable sequence of temporal phases, beginning with the green phase (healthy, un-attacked, and living trees), and progressing through red (dead, retaining foliage, and fine twigs), and gray phases (dead, with foliage and twigs having fallen to the ground). Other researchers (Jolly et al., 2012; Simard et al., 2011) have further separated the initial phases immediately after the initiation of the outbreak based on changes in foliar moisture content and the amount of canopy foliage that remains in the tree (e.g., very recently attacked trees that are beginning to lose canopy foliar moisture are often called yellow trees). Although the use of these temporal phases clearly shows how the fuels complex is altered at fine spatial scales associated with individual trees, alterations of the fuels complex at larger stand and landscape scales necessitates the spatial integration of such fine-scale changes across the stand. Complicating the ability to spatially integrate the effect of bark beetles on individual trees to larger areas is the fact that bark beetles have been shown to be selective in their attack strategy across stands and landscapes resulting in a mosaic of tree mortality (Bone et al., 2013), and that the mortality of individual trees within an area can occur over many years resulting in various mixtures of trees in different phases (Hicke et al., 2012). Stand and landscape-scale changes in the fuels complex, fire weather, and the potential fire behavior will therefore evolve following the initiation of an outbreak as a function of the rate and pattern of individual tree mortality. Yet very little work has attempted to quantify the effects of different rates and patterns of mortality on changes in the fuels complex, wind flow or fire behavior.

Previous simulation studies have suggested that changes in the fuels complex at the stand and landscape scales result in increased crown fire behavior for time periods immediately following the initiation of the outbreak when killed trees are in the red phase and there is a decrease in the mean foliar moisture content of the canopy (Page and Jenkins, 2007; Jenkins et al., 2008; Hicke et al., 2012; Hoffman et al., 2012a, 2013; Linn et al., 2013). Following the red stage, there is a decrease in crown fire potential when successfully killed trees have lost their foliage, and thus, reduced the stand level canopy fuel loading and increased the stand level canopy foliar moisture content (Page and Jenkins, 2007; Jenkins et al., 2008; Klutsch et al., 2011; Hicke et al., 2012; Simard et al., 2011; Schoennagel et al., 2012). However, substantial gaps in our knowledge remain with respect to the role that temporal and spatial variation in mortality may have on the fuels complex, fire environment, and potential fire behavior. This knowledge gap is due, in part both, to a lack of empirical or experimental data in bark beetle-affected forests and to limitations of models being used to explore these influences. Much of the past research directed at this knowledge gap has been done with modeling systems based on linkages between Rothermel's (1972, 1991) surface and crown fire spread models and Van Wagner's (1977) crown fire initiation and spread models. Modeling systems based on these linkages do not account for the spatial heterogeneity of the fuels complex, the influence of the fuels complex on the spatial and temporal variability in wind flow, or the effect of fire-induced turbulence; thus, these models are limited in their ability to offer further insights into the potential role of spatial heterogeneity arising from various rates and magnitudes of bark beetle mortality on fire behavior.

Process or physics-based fire behavior models such as the Wildland–Urban-Interface Fire Dynamics Simulator (WFDS, Mell et al., 2007, 2009) and HIGRAD/FIRETEC (Linn, 1997; Linn and Cunningham (2005); Linn et al., 2005; Pimont et al., 2009), hereafter referred to as FIRETEC, have been recently developed with the purpose of modeling many of the physical phenomena and interactions that control the behavior of a wildfire. Models such as WFDS and FIRETEC explicitly resolve a coupled set of partial differential equations describing the major physical processes and their interactions that influence fire behavior as well as the vertical and horizontal heterogeneity of the fuels complex within a three dimensional grid. Such modeling frameworks allow for the constantly changing, interactive relationship between the fire, the environment, and fuels to be simulated and can provide a framework to begin to explore the effect of various spatiotemporal fuels complexes following bark beetle mortality on potential fire behavior. A detailed description of the theoretical and mathematical concepts in FIRETEC can be found in Linn (1997), Linn et al. (2005), Linn and Cunningham (2005), and Pimont et al. (2009); more detailed information on WFDS can be found in Mell et al. (2007, 2009). To date, only a few studies have used physics-based models to investigate the potential effects of heterogeneity in the fuels complex arising from bark beetle mortality on fire behavior. Hoffman et al. (2012a, 2013) used WFDS to investigate the effect of the magnitude of bark beetle mortality, the spatial arrangement of overstory trees, and the surface fireline intensity on fire behavior during time periods when there are mixtures of individual trees in the red and green phases. Their results suggested that the crown fire intensity and amount of canopy fuel consumption increased as a function of the level of mortality and that this effect was most pronounced under moderate conditions. Linn et al. (2013) utilized FIRETEC to investigate changes in wind flow and fire rate-of-spread along a temporal sequence following bark beetle mortality in highly heterogeneous pinyon–juniper (*Pinus edulis–Juniperus* spp.) woodland. Their results suggested that alterations in the heterogeneity of canopy foliar moisture resulted in increased fire rates-of-spread during the initial phases of an outbreak and the heterogeneous fuels complex resulting from bark beetle mortality altered wind flow and fire behavior for periods of time when there was a mixture of green and gray trees. Past studies such as these highlight the potential role of physics-based models to investigate the implications of heterogeneity on fire behavior following disturbances such as bark beetle outbreaks.

In this paper, we used field data to populate a simple probabilistic model for tree-to-tree beetle spread and attack to develop two attack trajectories. These two attack trajectories represented two spatial and temporal patterns of bark beetle mortality with different mixtures of individual trees in various phases. The first scenario represented a rapid, broad-scale mortality event that resulted in high rates of mortality over a short period of time and a stand structure that is best characterized as random or dispersed through space. In contrast, the second scenario had a lower overall rate of mortality over a longer temporal period that resulted in clumpy patches of aggregated tree mortality, and thus, more