Agricultural and Forest Meteorology 173 (2013) 139–153

Contents lists available at SciVerse ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

# Modeling wind fields and fire propagation following bark beetle outbreaks in spatially-heterogeneous pinyon-juniper woodland fuel complexes

Rodman R. Linn[a,*], Carolyn H. Sieg[b], Chad M. Hoffman[c], Judith L. Winterkamp[a], Joel D. McMillin[d]

[a] Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, NM 87544, USA
[b] USDA Forest Service Rocky Mountain Research Station, 2500 Pine Knoll Drive, Flagstaff, AZ 86001, USA
[c] Department of Forest and Rangeland Stewardship, Colorado State University, Fort Collins, CO 80523, USA
[d] USDA Forest Service Region 3 Forest Health Protection, 2500 Pine Knoll Drive, Flagstaff, AZ 86001, USA

ARTICLE INFO

*Article history:*
Received 25 May 2012
Received in revised form 5 November 2012
Accepted 14 November 2012

*Keywords:*
Heterogeneous woodlands
Bark beetle tree mortality
Fire behavior
FIRETEC
Wind turbulence

ABSTRACT

We used a physics-based model, HIGRAD/FIRETEC, to explore changes in within-stand wind behavior and fire propagation associated with three time periods in pinyon-juniper woodlands following a drought-induced bark beetle outbreak and subsequent tree mortality. Pinyon-juniper woodland fuel complexes are highly heterogeneous. Trees often are clumped, with sparse patches of herbaceous vegetation scattered between clumps. Extensive stands of dead pinyon trees intermixed with live junipers raised concerns about increased fire hazard, especially immediately after the trees died and dead needles remained in the trees, and later when the needles had dropped to the ground. Studying fire behavior in such conditions requires accounting for the impacts of the evolving heterogeneous nature of the woodlands and its influence on winds that drive fires. For this reason we used a coupled atmosphere/fire model, HIGRAD/FIRETEC, to examine the evolving stand structure effects on wind penetration through the stand and subsequent fire propagation in these highly heterogeneous woodlands. Specifically, we studied how these interactions changed in woodlands without tree mortality, in the first year when dried needles clung to the dead trees, and when the needles dropped to the ground under two ambient wind speeds. Our simulations suggest that low wind speeds of 2.5 m/s at 7.5-m height were not sufficient to carry the fire through the discontinuous woodland stands without mortality, but 4.5 m/s winds at 7.5-m height were sufficient to carry the fire. Fire propagation speed increased two-fold at these low wind speeds when dead needles were on the trees compared to live woodlands. When dead needles fell to the ground, fine fuel loadings were increased and ambient wind penetration was increased enough to sustain burning even at low wind speeds. At the higher ambient wind speeds, fire propagation in woodlands with dead needles on the trees also increased by a factor of ~2 over propagation in live woodlands. These simulations indicate that sparse fuels in these heterogeneous woodlands can be overcome in three ways: by decreasing fuel moisture content of the needles with the death of the trees, by moving canopy dead needles to the ground and thus allowing greater wind penetration and turbulent flow into the woodland canopy, and increasing above-canopy wind speeds.



## 1. Introduction

Pinyon-juniper (*Pinus edulis-Juniperus* spp.) woodlands in the southwestern U.S. are extensive, covering >20 million ha in the region (Miller and Wigand, 1994). These woodlands are characterized by sparse surface fuels and discontinuous tree canopies that can curtail fire spread under low wind conditions (Floyd et al., 2008; Huffman et al., 2009; Miller et al., 2000; Romme et al., 2009). Extensive outbreaks of native bark beetles in recent decades have impacted coniferous ecosystems from Mexico to Alaska, including pinyon-juniper woodlands in the southwestern US (Bentz et al., 2009). A severe drought in 2002–2003 and the associated pinyon ips (*Ips confusus* LeConte) outbreak resulted in the mortality of a large number of pinyon trees across the southwestern US (Breshears et al., 2005; Shaw et al., 2005). The implications of such a large scale mortality event, although largely speculative in nature, are that they increase the potential for large, high-severity fires, especially given parallel trends of earlier and longer fire seasons in many coniferous forest types (Westerling et al., 2006) and projections of warmer and drier climates in the future (IPCC, 2007). Understanding the various physical mechanisms and interactions through which widespread bark-beetle outbreaks and the

* Corresponding author. Tel.: +1 505 665 6254; fax: +1 505 665 3285.
*E-mail addresses:* rrl@lanl.gov (R.R. Linn), csieg@fs.fed.us (C.H. Sieg), c.hoffman@colostate.edu (C.M. Hoffman), judyw@lanl.gov (J.L. Winterkamp), jmcmillin@fs.fed.us (J.D. McMillin).

0168-1923/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.agrformet.2012.11.007

resulting tree mortality alter fire behavior is important in order to inform future decisions about fire risk and fuels management in affected areas.

Two of the effects of tree mortality resulting from bark beetles are (1) the transition of foliage from live to dead fuels and an associated reduction in moisture content, and (2) changes in fuel arrangement when needles fall to the ground. Fire hazard is thought to increase immediately after mortality, when the dead and dry canopy fuels are present (Hicke et al., 2012; Jenkins et al., 2012; Keane et al., 2008), due to the decreased energy required to ignite the fuel and resulting in an increased rate of spread (Page and Jenkins, 2007a; Romme et al., 2006; Schmid et al., 1992; Simard et al., 2010). However, as Hicke et al. (2012) review points out, the implications of fire hazard and propagation in this early-outbreak stage are not well understood. There also exists the notion that after the needles from killed trees have fallen to the surface, the resulting increase in surface fuels can lead to increased surface fire spread, which can in turn result in ignition of the remaining living trees (Allen, 2007). However, understanding changes in fire behavior related to needle fall is complex because both wind flows within the canopy and the spatial arrangement of the fine fuels are altered. It is thus important to account for vegetation/atmosphere/fire coupling when trying to understand the impacts of bark-beetle mortality on fire behavior.

In this paper we use HIGRAD/FIRETEC, a physics-based coupled fire/atmosphere model, to explore fire/vegetation/atmosphere interactions associated with a drought-induced *Ips* beetle outbreak and massive pinyon pine die-off in pinyon-juniper woodlands in northern Arizona. Our objectives were to examine changes in within-stand wind behavior and fire propagation associated with three time periods: in woodlands without tree mortality, in the first year when dried needles clung to the dead trees, and when the needles dropped to the ground. Two ambient wind speeds were used for these studies.

## 2. Background

The majority of research concerning the impacts of bark-beetle outbreaks on stand structure and fire behavior has been conducted in lodgepole pine (*Pinus contorta*), Douglas-fir (*Pseudotsuga menziesii*), and Engelmann spruce (*Picea engelmannii*)-subalpine fir (*Abies lasiocarpa*) forests (Derose and Long, 2009; Hoffman, 2011; Hoffman et al., 2012a,b; Jenkins et al., 2008; Page and Jenkins, 2007a; Romme et al., 2006; Simard et al., 2010). One exception is Hoffman et al. (2012a), who quantified impacts of bark beetles on ponderosa pine (*Pinus ponderosa*) fuel complexes but did not assess the impacts on fire behavior. Another is Clifford et al. (2008), who provided observational data on fuel complexes and preliminary fire behavior following a pinyon ips outbreak in pinyon-juniper woodlands in New Mexico, but did not attempt to account for spatial variability in the fuels complex or winds. Vegetation/atmosphere/fire coupling is closely tied to the structure of forests and woodlands, which controls both the fire and the wind penetration into the canopy. Fires in pinyon-juniper woodlands, which have highly discontinuous canopy and surface fuels, should not be assumed to burn in the same manner as in forest types that have more continuous canopy or surface fuels.

The distribution and condition of the impacted fuels complexes, and likely thus the potential fire behavior, continue to evolve over time scales of years to tens of years after bark-beetle outbreaks (Hicke et al., 2012). This evolution can be considered in terms of three broadly simplified time periods. The first period is pre-outbreak, when trees are alive with green needles intact. The second period occurs in the first few years following a bark-beetle outbreak, and can be characterized by dramatic changes in fuel-moisture content as green needles on attacked trees die and their moisture levels drop to equilibrate with environmental conditions. The third time period is characterized by changes in fuel distribution as needles fall to the ground, which reduces canopy fuel continuity and oftentimes results in quite heterogeneous fuels complexes depending on the mixture of host and non-host species and the infestation patterns. As the needles fall to the ground, canopy-fuel loading and thus wind resistance within the crowns decreases, but surface-fuel loading increases (Page and Jenkins, 2007b). During this time period greater surface-fuel loading combined with greater penetration of ambient winds could increase surface fire spread under homogeneous stand conditions (Jenkins et al., 2008). However, the potential for the crown-fuel layer to support active fire spread is thought to decrease compared to pre-outbreak levels (Derose and Long, 2009; Jenkins et al., 2008; Page and Jenkins, 2007a; Simard et al., 2010).

Wind flows within forest canopies have been studied by a number of researchers using in situ and wind-tunnel measurements as well as numerical modeling tools; a description of some of these efforts in the context of this paper is provided in Appendix 1. Generally, shear and turbulent mixing are generated due to the interaction between fast moving air above the canopy top and canopy obstructions. The strength of the shear and mixing as well as the momentum exchange between winds above the vegetation and those within the canopy are affected by the scale and magnitude of canopy heterogeneities (Dupont and Brunet, 2006).

Changes in the dynamics of wind penetration through highly discontinuous woodlands have not been well characterized. Yet, it seems likely that modification of the turbulent mixing and coherent vortices that control the injection of horizontal momentum into the canopy, and the resulting shear profile within the canopy post-insect attack would combine to influence fire propagation. Unfortunately, the lack of either in situ experiments or computational fluid dynamis (CFD) modeling efforts focused on understanding winds in discontinuous vegetation types resembling pinyon-juniper woodlands in the southwestern US have thus far made it difficult to assess the changes in fire behavior that would follow such an outbreak in these ecosystems.

The processes that affect the ignition of unburned trees in front of a fire begin as radiative heat transfer warms the unburned fuel (Fig. 1). As energy is deposited in the unburned tree, the temperature increases and some of the moisture near the surface begins to evaporate; when sufficient net heat has been deposited on the surface, the fuel ignites. The net heat deposition is a balance between the heat deposited and that emitted to its surroundings, as discussed in more detail in Appendix 2.

In pinyon-juniper woodlands, where there is minimal surface fuel between the trees, the probability of fire spreading from tree to tree is dependent on the distance between trees and wind speeds within the canopy. When the flames and combustion gas plumes are angled more vertically, as occurs at lower wind speeds (the flame angle in Fig. 1, $\theta$, increases toward $90^{\circ}$), a shorter distance between trees, $d$, can be bridged by the propagating fire front. Crossstream-wind fluctuations determine the crossstream range of tree locations that can be heated by an upstream burning tree and the potential of fire spreading from tree to tree in directions other than directly downwind. Both streamwise and crossstream turbulence are affected by the homogeneity of the canopy fuel distribution. Previous studies (Parsons, 2007; Pimont et al., 2011) illustrated that changes in canopy structure, namely aggregation vs. even distribution of canopy vegetation, significantly impact fire spread in thinned treatment zones in dense pine stands with heavy and continuous surface fuels. Unfortunately, the results of these studies are not transferrable to pinyon-juniper woodlands, which are characterized by greater horizontal heterogeneity in overstory and surface fuels.