

**The Influence of Fuel Moisture and Flammable Monoterpenes
on the Combustibility of Conifer Fuels***

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Bark beetle-caused tree mortality and its effect on both the fuels complex and potential fire behavior in affected forests, particularly lodgepole pine forests, has been a topic of much debate in recent years (Hicke et al. 2012; Jenkins et al. 2012; Black et al. 2013). Early research on the subject seemed to suggest a straightforward relationship where it was expected that the tree mortality and its resulting direct and indirect effects on forest structure and fuel loading would increase potential fire behavior both in the short and long term (Brown 1975; Lotan et al. 1985; Schmid and Amman 1992). However, recent work has suggested a much more complicated relationship than previously thought that is dependent upon a host of site specific factors and the particular bark beetle-host system (Hicke et al. 2012; Donato et al. 2013). Of particular concern and the subject of most debate has been the influence of recent tree mortality on crown fire potential, including crown fire initiation and spread, in lodgepole pine forests, as

this forest type has been the most affected, in terms of area and severity, by mountain pine beetle-caused mortality. We argue that the use of inappropriate and/or un-validated fire behavior models based on inadequate descriptions of crown fuel flammability has been the primary source of confusion, which has led some to draw unsubstantiated conclusions. This work quantifies and clarifies some of the important changes to crown fuel flammability and crown fire potential caused by bark beetle attack so that more accurate assessments of crown fire potential can be made in the future.

Page et al. (2012 and 2014) presented results pertaining to the seasonal change in moisture content, chemistry, and flammability of foliage on bark beetle-attacked lodgepole pine and Engelmann spruce were presented. Several similarities between the tree species were found as well as some important differences that have implications on crown fire potential. Recently attacked lodgepole pine and Engelmann spruce foliage displayed substantial decreases in moisture content compared to un-attacked tree foliage, decreasing by a factor of 9 in lodgepole pine and 4 in Engelmann spruce foliage approximately 12 to 14 months following initial attack. Within the crowns of individual trees, lodgepole pine foliage required a slightly longer time period to express significant decreases in moisture content compared to Engelmann spruce foliage. By the end of the first fire season (October) in which the trees were initially attacked, lodgepole pine moisture content was still equivalent to the un-attacked foliage moisture content, however, the recently attacked Engelmann spruce foliage displayed patchy but significant declines in moisture content compared to un-attacked foliage. It was not until the early portion of the next fire season (i.e. spring) following the summer of initial attack that lodgepole pine foliage displayed significant declines in moisture content. Similar results were found when studying monoterpene and foliar moisture content in Douglas-fir trees attacked by Douglas-fir beetle

(Guinta et al. 2016 a and b).

Bark beetle-induced changes to foliar chemistry all three tree species studied closely followed observed changes in moisture content. During the process of dry-down the proportion of soluble carbohydrates and crude fat within the foliage of lodgepole pine and Engelmann spruce decreased while the proportion composed of the structural compounds of lignin and cellulose increased. These results were similar to those reported in litter decomposition studies where the proportion of dry matter composed of lignin was found to increase with time (e.g. Edmonds 1980). Additionally, terpenes including monoterpenes and sesquiterpenes, were found to be emitted at higher rates in recently attacked foliage on lodgepole pine but not on Engelmann spruce and correlated to needle flammability for both species. The combined effects of the changes in moisture content and chemistry resulted in substantial increases in foliage flammability, particularly ignitability, in both tree species.

Moisture content was found to be the most important variable affecting foliage flammability followed by the changes in foliar chemistry. Based on the reported results we suggested that there may be periods of enhanced potential for surface fires to transition to crown fires in stands containing significant amounts of bark beetle-altered foliage due to a lower canopy ignition threshold compared to un-attacked stands. This enhanced potential would be most acute under more moderate fire weather and stand conditions where surface fire intensity and/or canopy base height would normally limit crown fire initiation. However, this period of enhanced crown fire initiation is dependent upon both the time since attack and the particular trees species as it was found that the foliage on recently attacked Engelmann spruce only remained attached for a period of 12 to 14 following initial colonization by the beetle, suggesting

that once the needles drop to the forest floor, crown fire potential significantly decreases due to a decrease in aerial fuel continuity.

Given the importance of fuel moisture on the ignitibility of lodgepole pine foliage (Page et al. 2012), it was important that methods be developed to predict short-term (i.e. hourly) changes in moisture content that can be used to more accurately assess crown fire potential during operational time scales. Previous research has assumed that the moisture content of mountain pine beetle-attacked lodgepole pine tree foliage during the red stage is equivalent to the moisture content of other fine dead surface fuels (e.g. Hoffman et al. 2012; Schoennagel et al. 2012). Most fine dead surface fuels show strong diurnal trends in moisture content as they respond to increasing atmospheric moisture during the night and lower moisture during the day (Hartford and Rothermel 1991). This daily trend in moisture content usually corresponds to periods of decreased fire behavior at night and peaks in fire behavior during the afternoon. The results from Page et al. (2014) showed that many of the models used to estimate fine dead fuel moisture in Australia, Canada, and the USA are inadequate for predicting the moisture content of dead lodgepole pine foliage due to the lack of diurnal variation, with significant under- and over-prediction biases during periods of low and high atmospheric moisture, respectively.

Due to the poor predictions obtained from existing fine fuel moisture models it was necessary to develop and test new models or calibrate existing models. Additional field sampling was carried out to capture a wider range of air temperature and relative humidity than observed by Page et al. (2014a) to develop more robust models (Page et al. 2014b). Five models in total were developed and evaluated including three bookkeeping-type system models based on diffusion theory that used previously identified model forms (e.g. Catchpole et al. 2001) and two calibrated operational models commonly used in the USA and Canada. All models performed

well compared to the test dataset with the calibrated operational models performing as good or better than the more complicated models bookkeeping-type system models. Based on these results we recommended that fire managers use the calibrated operational models to predict the moisture content of red and dead foliage on mountain pine beetle-attacked lodgepole pine due to their high accuracy and ease of use.

Page et al. (2014c) reviewed the literature on the subject of crown fire potential in recently attacked, mountain pine beetle-infested lodgepole pine forests during the red stage using the results from our previous work and other pertinent research. We found inconsistent results in the literature due to the use of inappropriate and/or un-validated fire behavior models that used inadequate descriptions of the mountain pine beetle- affected crown and canopy fuels. We suggested that crown fire initiation and spread potential is higher in recently attacked forests compared to un-attacked forests and that a host of site specific factors such as outbreak severity, timing, and length could have important but as yet unknown impacts based on a set of limited fire behavior observations and re-examination of fire behavior modeling methodology. Due to the limitations of current fire behavior models and lack of quality data we propose that further advances in our knowledge of crown fire potential in recently attacked forests will only be possible if a substantial effort is undertaken to document wildfires or conduct experimental fires.

Bark beetles are a natural disturbance agent in the conifer forests of western North America having caused periods of significant tree mortality for thousands of years (e.g. Brunelle et al. 2008). Thus the relatively recent tree mortality caused by eruptive outbreaks of these beetles and the direct and indirect effects on forest structure and fire behavior should also be considered a natural part of the life history of these forests (Brown 1975; Lotan et al. 1985). Although the changes to forest structure, fuel loading, and subsequent fire behavior caused by

the tree mortality are considered natural, there are significant consequences of these changes related to human factors such as wildland firefighter safety and suppression operations (Page et al. 2013). Fire managers and wildland firefighters should be cognizant of the impacts of recent tree mortality on potential fire behavior regardless of whether the changes are considered natural.

Therefore, it is important that research be undertaken, as presented here and elsewhere, to quantify and understand the various factors affected by bark beetle-caused tree mortality that impact potential fire behavior and the consequences of those changes for wildland firefighters. Given that there are still substantial uncertainties associated with crown fire potential in recently attacked forests, wildland firefighters should continue to be cautious when working in these forests and prepare for fire behavior that is not easily predicted using conventional operational models.

Deliverables;

Nine peer reviewed published papers, a Ph.D. dissertation and a M.S. Thesis have been delivered on this project. These papers are posted to the JFSP website providing detailed explanations of methods and results and the three bark beetle/host systems studied.

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