Effects of Bark Beetle Attack on Canopy Fuel Flammability and Crown Fire Potential in Lodgepole Pine and Engelmann Spruce Forests

Wesley G. Page, Department of Wildland Resources, Utah State University, Logan, UT; **Martin E. Alexander,** Department of Renewable Resources and Alberta School of Forest Science and Management, University of Alberta, Edmonton, AB and Department of Wildland Resources, Utah State University, Logan, UT; and **Michael J. Jenkins**, Department of Wildland Resources, Utah State University, Logan, UT

Abstract—*Large wildland fires in conifer forests typically involve some degree of crowning, with their initiation and propagation dependent upon several characteristics of the canopy fuels. Recent outbreaks of mountain pine beetle (*Dendroctonus ponderosae *Hopkins) in lodgepole pine (*Pinus contorta *Dougl. var.* latifolia *Engelm.) forests and spruce beetle (*Dendroctonus rufipennis *Kirby) in Engelmann spruce (*Picea engelmannii *Parry ex Engelm.) forests have affected vast areas across western and northern North America, which have subsequently produced forests containing relatively large amounts of dead or "bark beetle-altered" canopy fuel. Given that the transition to crowning represents an important threshold in terms of large fire growth and wildland firefighter safety and effectiveness, a better understanding of the potential role of bark beetle-altered foliage in altering crown fire initiation and spread is needed. This paper summarizes a recently completed research project dealing with the measurement and characterization of the changes in crown fuel flammability caused by recent bark beetle attacks and consequently the implications of these changes on crown fire potential in these affected forest types.*

Introduction

Recent epidemics of various bark beetles species in the genus *Dendroctonus* have caused widespread tree mortality in their respective conifer hosts across western North America (Meddens and others 2012). Bark beetle-caused tree mortality and its effect on both the fuels complex and potential fire behavior in affected forests, particularly in lodgepole pine forests (Fig. 1), has been a topic of much debate in recent years (Jenkins and others 2008, 2012, 2014b; Hicke and others 2012; Black and others 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 loads would increase potential fire behavior both in the short and long term (Brown 1975; Lotan and others 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 and others 2012; Donato and others 2013). Of particular concern and the subject of most debate has been the influence of recent tree mortality on canopy fuel flammability and crown fire potential, including crown fire initiation and spread, in lodgepole pine forests.

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

The work by Page (2014a) represents an attempt to quantify and clarify 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. This research first involved a comprehensive literature review on the general topic area—i.e., the effects of bark beetle attack on fuel characteristics and fire dynamics in lodgepole pine and Engelmann spruce forests, especially as it pertains to crowning phenomena (Jenkins and others 2012, 2014a). This was in turn followed by answering four primary research questions based on the results of extensive field and lab work conducted in both lodgepole pine and Engelmann spruce dominated forests (Box 1):

- How does successful attack by mountain pine beetle in lodgepole pine and spruce beetle in Engelmann spruce trees alter the moisture content, chemistry, and flammability of foliage over time?
- How does the moisture content of dead foliage on lodgepole pine trees during the red stage of mountain pine beetle attack change diurnally?
- Can models be developed to predict the hourly change in moisture content of foliage on lodgepole pine trees during the red stage?
- What are the consequences of mountain pine beetle-caused changes to crown and canopy fuels on crown fire initiation and spread in lodgepole pine forests?

In this paper we provide a summary of the results of the analysis undertaken by Page (2014a) organized along the

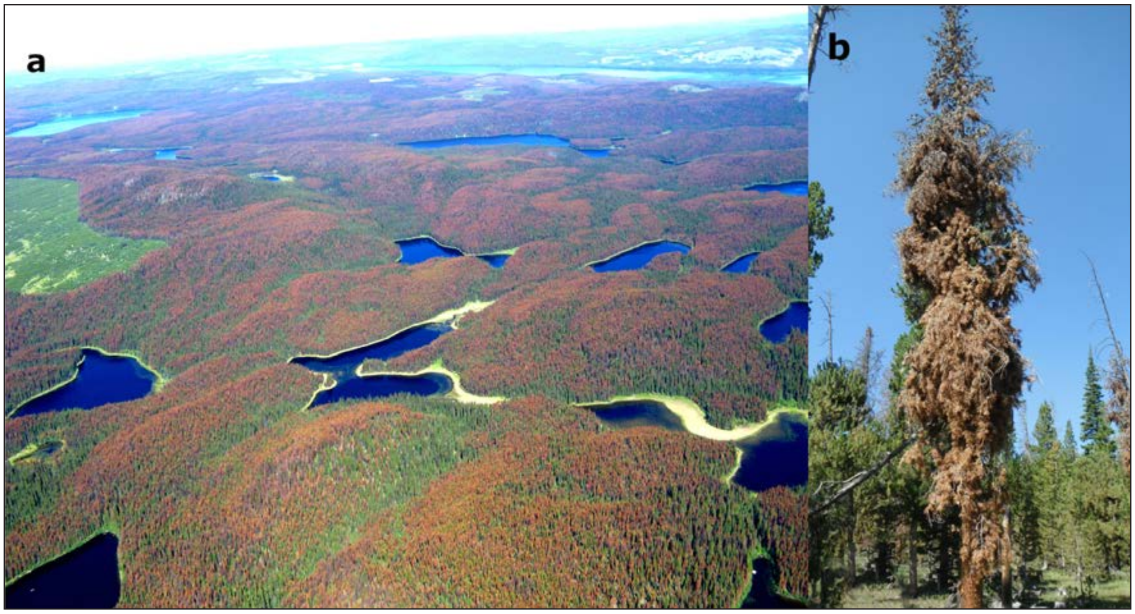

Figure 1—Lodgepole pine during the red stage of mountain pine beetle attack (a) at the landscape scale in British Columbia, Canada (from Woods and others 2010; photo by L. Maclauchlan, British Columbia Ministry of Forests and Range) and (b) at the individual tree level in northeastern Utah (photo by W.G. Page).

lines of the primary topics, namely, the seasonal changes in moisture, chemistry, and flammability of bark beetle-attacked foliage on lodgepole pine and Engelmann spruce trees (Fig. 2), the diurnal changes in moisture content of lodgepole pine foliage during the red stage of mountain pine beetle attack (Fig. 1), and the implications of those changes on crown fire initiation and spread in lodgepole pine forests. Additionally, a number of research needs and knowledge gaps are highlighted. Finally, we frame these results along with additional information about the effects of mountain pine beetle-caused tree mortality over longer time frames (i.e., during the gray and post-epidemic stages) within the context of the concept of wildfire resistance to control.

Figure 2—Engelmann spruce foliar moisture and chemistry sampling study site on the Heber-Kamas Ranger District of the Uinta-Wasatch-Cache National Forest in northern Utah (photo by W.G. Page).

For a popularized summary of the research carried out by Page (2014a), refer to the article published in *Utah Forest News* by Page (2014b). Copies of all of the articles associated with the research project and including Page (2014a) are available at: http://digitalcommons.usu.edu/barkbeetles/.

Seasonal Changes in Moisture Content, Chemistry and Flammability of Lodgepole Pine and Engelmann Spruce Foliage

The detailed results pertaining to the seasonal change in moisture content, chemistry, and flammability of foliage on bark beetle-attacked lodgepole pine and Engelmann spruce forests were presented by Page and others (2012, 2014a). The sampling of the lodgepole pine took place on the Palisades Ranger District of the Caribou-Targheee National Forest in eastern Idaho during the summer of 2011 and in Engelmann spruce on the Heber-Kamas Ranger District of the Unita-Wasatch-Cache National Forest in northern Utah during the summer of 2012. The fuel moisture sampling in lodgepole pine supplements the similar work carried out in lodgepole pine in north-central Colorado and western Montana by Jolly and others (2012).

Several similarities between the two 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

Box 1. Summary of the conclusions and implications associated with the four primary research questions (from Page 2014a).

1. *How does successful attack by mountain pine beetle in lodgepole pine and spruce beetle in Engelmann spruce trees alter the moisture content, chemistry, and flammability of foliage over time?* Conclusions:

- There are significant declines in the moisture content of foliage for both species with most of the decline occurring within 12 to 14 months after initial attack.
- A shift in foliar chemistry occurs for both species with higher proportions of carbohydrates and crude fat in unattacked foliage and lower proportions of those compounds in foliage on attacked trees.
- There is a significant increase in foliar flammability, particularly ignitability, due primarily to the decrease in moisture content.

Implications: The high ignitability of foliage on attacked trees could lead to a decrease in the canopy ignition threshold in stands containing high proportions of bark beetle-altered foliage, and therefore an increase in the potential for crown fire initiation.

2. *How does the moisture content of dead foliage on lodgepole pine trees during the red stage of mountain pine beetle attack change diurnally?* Conclusions:

- Contrary to other fine dead surface fuels like needle litter, the red foliage on mountain pine beetle-killed lodgepole pine trees does not have significant diurnal variation.
- Existing models used to predict the hourly changes in moisture content of other fine dead fuels are inadequate.

Implications: The high ignitability of the red foliage could extend into the overnight or early morning hours, thereby potentially lengthening the window of crown fire activity.

3. *Can models be developed to predict the hourly change in moisture content of foliage on lodgepole pine trees during the red stage?* Conclusions:

- The red foliage does dry following a typical exponential decline thereby allowing for the development of diffusion-based bookkeeping-type system models.
- Calibrated operational fine fuel moisture models performed as well or better than the more complicated bookkeeping-type system models.
- Model evaluation indicated that the proposed models may be limited in geographic applicability to the Intermountain region of the western United States.

Implication: We recommend that the calibrated operational fine fuel moisture models be used by field personnel.

4. *What are the consequences of mountain pine beetle-caused changes to crown and canopy fuels on crown fire initiation and spread in lodgepole pine forests?* Conclusions:

- Bark beetle attack produces stands with highly heterogeneous and complex canopy fuel conditions.
- Existing semi-empirical and empirical-based fire behavior models are inadequate for accurately assessing crown fire potential in recently attacked lodgepole pine forests.
- Outputs from physics-based fire behavior models should be viewed with caution as these models have yet to be evaluated in conifer forests containing either live or dead canopy fuel.

Implications: Our understanding of crown fire dynamics in recently attacked lodgepole pine forests will not substantially improve until a significant effort is made to collect field-based observations of fire behavior to either evaluate existing models or develop new ones.

individual trees, lodgepole pine foliage required a slightly longer time period to express significant decreases in moisture content compared to Engelmann spruce foliage (Fig. 2). 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.

Bark beetle-induced changes to foliar chemistry for both tree species closely followed observed changes in moisture content. During the process of dry-down, the proportion of soluble carbohydrates and crude fat within the foliage 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, however, they were found to play significant roles in 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 potential 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 months 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 canopy fuel density and continuity. Although, it should be noted that this outcome could be site specific as other bark beetle-affected spruce forests can retain significant vertical canopy fuel continuity in the form of small diameter branch wood after the needles have dropped to the ground (Alexander and Stam 2003; Hawkes and others 2014)

Diurnal Changes in Lodgepole Pine Foliar Moisture Content

Given the importance of fuel moisture on the ignitibility of lodgepole pine foliage as demonstrated by Page and others (2012) and Jolly and others (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 and others 2012; Schoennagel and others 2012). This assertion was partly based on the fact that most fine dead surface fuels show strong diurnal changes in moisture content as they respond to increasing atmospheric moisture during the night and lower moisture during the day (Steen 1963; 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.

Diurnal sampling in lodgepole pine was undertaken in the Evanston-Mountain View Ranger District of the Uinta-Wasatch-Cache National Forest in north-eastern Utah in late May and early August of 2012. The results from Page and others (2013a) 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 "red and dead" lodgepole pine needle foliage (Fig. 1) due to the lack of diurnal variation, with significant under- and over-prediction biases during periods of low and high atmospheric moisture, respectively. This includes the Rothermel (1983) fine dead fuel moisture table procedure, which has been suggested as a way to estimate the moisture content of "red and dead" foliage in order to determine the probability of ignition of red attack stage trees (Hoyt and Jolly 2012).

Due to the poor predictions obtained from existing fine fuel moisture models, it was found necessary to develop and test new models or to calibrate existing models. Additional field sampling was carried out to capture a wider range of air temperature and relative humidity than observed by Page and others (2013a) in order to develop more robust models (Page and others 2015). Sampling took place on the Laramie Ranger District of the Medicine Bow-Routt National Forest in south-eastern Wyoming over the course of the summer of 2013.

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 and others 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 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.

Crown Fire Potential in Lodgepole Pine Forests

It has previously been demonstrated that bark beetle-caused tree mortality can cause significant changes to stand structure, woody surface fuel loads, and canopy fuel loads and arrangement (Jenkins and others 2008; Hicke and others 2012). The effects of those changes on potential surface fire behavior are generally believed to be dependent upon the time since mortality, the relative concentration of fine fuel accumulation, and microclimatic changes within affected stands that can cause variations in surface fuel moisture and in-stand wind speed conditions (Jenkins and others 2008). What remains unclear however, are the possible alterations to crown fire potential as bark beetle-infested trees undergo changes in their physical and chemical characteristics as they proceed from their healthy or unattacked state to their "red" condition.

Drawing upon the results of Page and others (2012, 2013a, 2014a, 2014c) as well as other pertinent literature, Page and others (2014b) completed a critical review and digest of the literature on the subject of crown fire potential in recently attacked, mountain pine beetle-infested lodgepole pine forests during the red stage of attack. They found inconsistent results in the literature due to the use of inappropriate and/or un-validated fire behavior models based on inadequate descriptions of the mountain pine beetle-affected crown and canopy fuels. Van Wagner's (1977) crown fire initiation model, for example, in its present or some modified form is not applicable to mountain pine beetle-attacked stands because their very low foliar moisture content levels are not in aligned with the model parameterizing (Cruz and Alexander 2010).

Page and others (2014b) 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 understanding of crown fire potential in recently attacked forests will only be possible if a substantial effort is undertaken to document wildfires, prescribed fires, and/or conduct experimental fires.

Addressing Future Research Needs and Knowledge Gaps

As described by Page and others (2014b), the study of crown fire potential in recently attacked, bark beetle-infested stands will not be able to substantially progress until wildfire observations and/or experimental fires can be used to quantify several important fire behavior metrics, including, rate of spread, fireline intensity, fuel consumption, flame front residence time, and burn-out time under a variety of weather and stand conditions. Ideally, stands with varying amounts and proportions of bark beetle-altered foliage, distributed spatially in arrangements from random to highly clustered would be subjected to fire in order to quantify the relative impact of both the amount of red foliage and its spatial distribution. This would allow wildland firefighters to identify and rank the relative hazard of stands, in terms of crowning potential, containing the variety of mortality levels and spatial arrangements that are found naturally in forested landscapes. For example, we may eventually find that a critical level of red foliage exists such that until that level is reached, bark beetle-caused tree mortality may have little effect on crown fire initiation or spread. Additionally, we may also find that the spatial arrangement of the mortality within a stand (either highly clustered or randomly distributed) may have little overall impact on fire behavior. These questions can only truly be answered in the field, particularly as they relate to wildland firefighter safety and operations, which is where the need for such research ultimately arises. However, this does not preclude the use of physics-based models as a valuable research tool in these forests (Hoffman and others 20120) but even those models must be evaluated against field data in order to feel confident in their use, especially when it comes to firefighter safety.

Wildfire Resistance to Control in Lodgepole Pine Forests

Concerns about the impacts of mountain pine beetle-caused tree mortality on wildfire potential in lodgepole pine forests have to date largely focused on the potential for extreme fire behavior, including the development and spread of crown fires. Given that the fire environment in which wildland fire managers and firefighters work is composed of many interacting physical and human factors, viewing crown fire behavior as the only or even the most important outcome of the tree mortality associated with a mountain pine beetle outbreak is questionable. Proper assessment of wildfire potential entails a broader approach, which requires expanding the concept of wildfire resistance to control to include an analysis of all relevant factors and their interactions. In this regard, Page and others (2013b) advocated a holistic approach to analyzing the impacts of mountain pine beetle-caused tree mortality on wildfire potential in lodgepole pine forests on the basis of fire behavior characteristics, fire suppression operations, and firefighter safety considerations within the framework of the three recognizable stages of the approximate time since the initiation of an outbreak: "red" (~1 to 5 years), "gray" (~5 to 15 years), and post-epidemic (~15+ years).

Conclusions

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 and others 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 (Wright and Heinselman 1973; Brown 1975; Lotan and others 1985).

Although the changes to forest structure, fuel loads, 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 fire suppression operations (Page and others 2013b). Fire managers and wildland firefighters alike should be cognizant of the impacts of recent tree mortality on potential fire behavior regardless of whether the changes are considered natural or not. Therefore, it is important that the research be undertaken, as outlined by Page and others (2013a, 2013b, 2014b), 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 (Moriarty 2014).

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 fire behavior models and guidelines. It is only very recently that a rough guide to crown fire initiation and a model for predicting crown fire rate of spread for the red stage of bark beetle-attacked lodgepole pine forests has been developed in the context of the Canadian Forest Fire Danger Rating System (Perrakis and others 2014).

Acknowledgment

This work was supported by the Joint Fire Science Program projects JFSP 11-1-4-16 (MJJ) and JFSP 09-S-03-1 (MEA). The reviews by B.C. Hawkes and D.T. Hicks are hereby duly noted.

References

Alexander, Martin E.; Stam, Joseph C. 2003. Safety alert for wildland firefighters: fuel conditions in spruce-beetle-killed forests. Fire Management Today. 63(2): 25.

Black, Scott H.; Kulakowski, Dominik; Noon, Barry R.; DellaSala, Dominick A. 2013. Do bark beetle outbreaks increase wildfire risks in the central U.S. Rocky Mountains? Implications from recent research. Natural Areas Journal. 33: 59-65.

Brown, James K. 1975. Fire cycles and community dynamics in lodgepole pine forests. In: Baumgartner, David M., ed. Management of lodgepole pine ecosystems: symposium proceedings, volume II; 1973 October 9-11; Pullman, WA. Pullman, WA: Washington State University, Cooperative Extension Service: 429-456.

Brunelle, Andrea; Rehfeldt, Gerald E.; Bentz, Barbara; Munson, A. Steven. 2008. Holocene records of Dendroctonus bark beetles in high elevation pine forests of Idaho and Montana, USA. Forest Ecology and Management. 255: 836-846.

Catchpole, E.A.; Catchpole, W.R.; Viney, N.R.; McCaw, W.L.; Marsden-Smedley, J.B. 2001. Estimating fuel response time and predicting fuel moisture content from field data. International Journal of Wildland Fire. 10: 215-222.

Cruz, Miguel G.; Alexander, Martin E. 2010. Assessing crown fire potential in coniferous forests of western North America: a critique of current approaches and recent simulation studies. International Journal of Wildland Fire. 19: 377-398.

Donato, Daniel C.; Harvey, Brian J.; Romme, William H.; Simard, Martin; Turner, Monica G. 2013. Bark beetle effects on fuel profiles across a range of stand structures in Douglas-fir forests of Greater Yellowstone. Ecological Applications. 23: 3-20.

Edmonds, Robert L. 1980. Litter decomposition and nutrient release in Douglas-fir, red alder, western hemlock, and Pacific silver fir ecosystems in western Washington. Canadian Journal of Forest Research. 10: 327–337.

Hartford, Roberta A.; Rothermel, Richard C. 1991. Fuel moisture as measured and predicted during the 1988 fires in Yellowstone National Park. Res. Note INT-396. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 7 p.

Hawkes, Brad; Alfaro, René; Waring, Vince; Berg, Jenny. 2014. Response of southwest Yukon forests to spruce beetle: 2010 plot re-assessment. Inf. Rep. BC-X-435. Victoria, BC: Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre. 38 p.

Hicke, Jeffrey A.; Johnson, Morris C.; Hayes, Jane L.; Preisler, Haiganoush K. 2012. Effects of bark beetle caused tree mortality on wildfire. Forest Ecology and Management. 271: 81-90.

Hoffman, Chad; Morgan, Penny; Mell, William; Parsons, Russell; Strand, Eva K.; Cook, Stephen. 2012. Numerical simulation of crown fire hazard immediately after bark beetle-caused mortality in lodgepole pine forests. Forest Science. 58: 178-188.

Hoyt, Stu; Jolly, Matt. 2012. Probability of ignition of mountain pine beetle affected trees. Available at: http://gacc.nifc.gov/swcc/predictive/fuels_fire-danger/hot_topics/2012/Probability%20of%20Ignition%20of%20Mountain%20Pine%20Beetle%20Affected%20Trees.pdf

Jenkins, Michael J.; Hebertson, Elizabeth; Page, Wesley; Jorgensen, C. Arik. 2008. Bark beetles, fuels, fires and implications for forest management in the Intermountain West. Forest Ecology and Management. 254: 16–34.

Jenkins, Michael J.; Page, Wesley G.; Hebertson, Elizabeth G.; Alexander, Martin E. 2012. Fuels and fire behavior dynamics in bark beetle-attacked forests in Western North America and implications for fire management. Forest Ecology and Management. 275: 23-34.

Jenkins, Michael J.; Hebertson, Elizabeth G.; Munson, A. Steven. 2014a. Spruce beetle biology, ecology and management in the Rocky Mountains: an addendum to spruce beetle in the Rockies. Forests. 5:21-71.

Jenkins, Michael J.; Runyon, Justin B.; Fettig, Christopher J.; Page, Wesley G.; Bentz, Barbara J. 2014b. Interactions among the mountain pine beetle, fires, and fuels. Forest Science. 60: 489-501.

Jolly, W. Matt; Parsons, Russell A.; Hadlow, Ann M.; Cohn, Greg M.; McAllister, Sara S.; Popp, John B.; Hubbard, Richard M.; Negron, José F. 2012. Relationships between moisture, chemistry, and ignition of Pinus contorta needles during the early stages of mountain pine beetle attack. Forest Ecology and Management. 269: 52-59.

Lotan, James E.; Brown, James K.; Neuenschwander, Leon F. 1985. Role of fire in lodgepole pine ecosystems. In: Baumgartner, David M.; Krebill, Richard G.; Arnott, James T.; Weetman, Gordon F., eds. Lodgepole pine: the species and its management symposium proceedings; 1984 May 8-10, Spokane, WA; 1984 May 14-16, Vancouver, BC. Pullman, WA: Washington State University, Office of Conferences and Institutes: 133-152.

Meddens, Arjan J.H.; Hicke, Jeffrey A.; Ferguson, Charles A. 2012. Spatiotemporal patterns of observed bark beetle-caused tree mortality in British Columbia and the western United States. Ecological Applications. 22: 1876-1891.

Moriarty. Kevin. 2014. Firefighter observations on mountain pine beetle post-outbreak lodgepole pine fires: expectations, surprises and decision-making. Fort Collins, CO: Colorado State University. 45 p. M.Sc. Thesis.

Page, Wesley G. 2014a. Bark beetle-induced changes to crown fuel flammability and crown fire potential. Utah State University, Logan, UT. 254 p. Ph.D. Dissertation.

Page, Wesley G. 2014b. Bark beetles and crown fire hazard. Utah Forest News 18(1): 4-5.

Page, Wesley G.; Jenkins, Michael J.; Runyon, Justin B. 2012. Mountain pine beetle attack alters the chemistry and flammability of lodgepole pine foliage. Canadian Journal of Forest Research. 42: 1631-1647.

Page, Wesley G.; Jenkins, Michael J.; Alexander, Martin E. 2013a. Foliar moisture content variations in lodgepole pine over the diurnal cycle during the red stage of mountain pine beetle attack. Environmental Modelling & Software. 49: 98-102.

Page, Wesley G.; Alexander, Martin E.; Jenkins, Michael J. 2013b. Wildfire's resistance to control in mountain pine beetle-attacked lodgepole pine forests. Forestry Chronicle. 89: 783-794.

Page, Wesley G.; Jenkins, Michael J.; Runyon, Justin B. 2014a. Spruce beetle-induced changes to Engelmann spruce foliage flammability. Forest Science. 60: 691-702.

Page, Wesley G.; Jenkins, Michael J.; Alexander, Martin E. 2014b. Crown fire potential in lodgepole pine forests during the red stage of mountain pine beetle attack. Forestry. 87: 347-361.

Page, Wesley G.; Jenkins, Michael J.; Alexander, Martin E. 2015. Models to predict the moisture content of lodgepole pine foliage during the red stage of mountain pine beetle attack. Forest Science. 61: 128-134.

Perrakis, Daniel D.B.; Lanoville, Rick A.; Taylor, Stephen W.; Hicks, Dana. 2014. Modeling wildfire spread in mountain pine beetle-affected forest stands, British Columbia, Canada. Fire Ecology. 10(2): 10-35.

Rothermel, Richard C. 1983. How to predict the spread and intensity of forest and range fires. Gen. Tech. Rep. INT-143. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 161 p.

Schmid, J.M.; Amman, G.D. 1992. Dendroctonus beetles and old-growth forests in the Rockies. In: Kaufmann, M.R.; Moir, W.H.; Bassett, R.L., tech. eds. Proceedings of a workshop, Old-growth forests in the Southwest and Rocky Mountain regions: proceedings of a workshop; 1992 March 9-13. Gen. Tech. Rep. RM-213. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 51-59.

Schoennagel, Tania; Veblen, Thomas T.; Negron, José F.; Smith, Jeremy .M. 2012. Effects of mountain pine beetle on fuels and expected fire behavior in lodgepole pine forests, Colorado, USA. PLoS ONE. 7: e30002.

Simard, Martin; Romme, William H.; Griffin, Jacob M.; Turner, Monica G. 2011. Do mountain pine beetle outbreaks change the probability of active crown fire in lodgepole pine forests? Ecological Monographs. 81: 3-24.

Steen, Harold K. 1963. Relation between moisture content of fine fuels. Res. Note PNW-4. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 6 p.

Van Wagner, C.E. 1977. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research. 7: 23-34.

Woods, Alex J.; Heppner, Don ; Kope, Harry H.; Burleigh, Jennifer; Maclauchlan, Lorraine. 2010. Forest health and climate change: a British Columbia perspective. Forestry Chronicle. 86: 412-422.

Wright, H.E., Jr.; Heinselman, M.L. 1973. The ecological role of fire in natural conifer forests of western and northern North America—introduction. Quaternary Research. 3: 319-328.

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.