Forestry Advance Access published February 18, 2014

Forestry An International Journal of Forest Research

Institute of Chartered Foresters

Forestry 2014; **0**, 1–15, doi:10.1093/forestry/cpu003

Crown fire potential in lodgepole pine forests during the red stage of mountain pine beetle attack

Wesley G. Page[1], Michael J. Jenkins[1]* and Martin E. Alexander[1,2]

[1]*Department of Wildland Resources, Utah State University, Logan, UT, USA 84322*
[2]*Department of Renewable Resources and Alberta School of Forest Science and Management, University of Alberta, Edmonton, AB, Canada T6G 2H1*

*Corresponding author Tel.: +1 4357972531; Fax: +1 4357973796; E-mail: mike.jenkins@usu.edu

Received 10 November 2013

Mountain pine beetle (MPB) outbreaks within the previous 10–15 years have affected millions of hectares of lodgepole pine forests in western North America. Concerns about the influence of recent tree mortality on changes in fire behaviour amongst firefighters and fire managers have led researchers to attempt to quantify the effects on crown fire potential. In this paper we provide an up-to-date review and critique of research that has endeavoured to quantify the effect of recent MPB-caused tree mortality, during the red stage, on crown fire potential based upon quantitative descriptions of important crown and canopy fuel characteristics and simulation-based assessments of crown fire initiation and spread using operational and physics-based models. While significant progress has been made in characterizing the important variables affecting crown fire potential in recently attacked forests, we suggest that many of the conclusions drawn from simulation-based studies conducted to-date are suspect given the use of inappropriate and/or un-validated models. A systematic program of experimental burning, the monitoring and documentation of wildfires and prescribed fires, and better models of fuel moisture and fuel structure are urgently needed in order to properly assess crown fire potential in lodgepole pine forests recently attacked by the MPB.

Introduction

Lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) forests in western North America have recently experienced widespread and severe tree mortality caused by mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins). High levels of tree mortality in susceptible stands occurred in British Columbia, Canada, during the early 2000s and more recently in the western US, affecting >7 million hectares (Meddens *et al.*, 2012). The warming observed during the last few decades has led some to suggest that climate change may be contributing to the current severity of MPB outbreaks and on-going range expansion to northern British Columbia and east into Alberta (Bentz *et al.*, 2010; Safranyik *et al.*, 2010). While the majority of the tree mortality has passed its peak levels in western North America, there are concerns that the outbreak will continue to extend east across Canada and involve jack pine (*P. banksiana* Lamb.) forests (Cullingham *et al.*, 2011).

Given the current and potential future impacts of MPB-caused tree mortality on lodgepole pine forests, several studies have been undertaken to describe the changes in fuels and potential fire behaviour (e.g. Page and Jenkins, 2007a, b; Klutsch *et al.*, 2009, 2011; Simard *et al.*, 2011; Schoennagel *et al.*, 2012). Reviews by Jenkins *et al.* (2008, 2012, 2014) and Hicke *et al.* (2012) have provided summaries of the applicable work related to MPB-caused tree mortality and its effect on fuels and potential fire behaviour through 30–40 years post-outbreak. Among these review papers was a general view that a period of enhanced crown fire potential exists during the red stage while the dead or 'red' needles are retained within the canopy (Figure 1a,b), generally considered to be a period of < 5–10 years after the first successful attacks, but that current gaps in our understanding exist due to unknowns associated with red needle flammability and its effect on crown fire initiation and spread (Jenkins *et al.*, 2008; Hicke *et al.*, 2012).

The above noted unknowns and confusion over terminology (i.e. risk *vs* hazard), coupled with the misapplication of operational fire behaviour models have led some (e.g. Simard *et al.*, 2011; Black *et al.*, 2013) to draw inappropriate conclusions (Jenkins *et al.*, 2012; Jolly *et al.*, 2012a). For example, Simard *et al.* (2011) and in turn Black *et al.* (2013) suggested on the basis of the results from their simulation modelling that there is not an increase in crown fire potential in recently attacked stands and therefore there is no need for management action to mitigate any potential dangers associated with wildfire. However, most observational evidence to-date does not support this assertion (e.g. Stiger and Infanger, 2011; Page *et al.*, 2013a). Additionally, there are other important implications of MPB-induced tree mortality on firefighter safety and suppression tactics, including, safety zone size, escape route designation and escape time, and overall suppression strategy that have significant consequences for wildland fire personnel (Page *et al.*, 2013a). Fortunately, fire management organizations in British Columbia and the western US have recognized the

© Institute of Chartered Foresters, 2014. All rights reserved. For Permissions, please e-mail: journals.permissions@oup.com.

Downloaded from http://forestry.oxfordjournals.org/ by guest on February 26, 2014

Figure 1 Photographs of MPB-affected (a) lodgepole pine stand on the Sawtooth National Recreation Area (SNRA), central ID, US, in July 2004 with unattacked (green) tree crowns intermixed with currently attacked trees, trees attacked the previous year (yellow), and trees attacked >2 years previously (red) (photo by M.J. Jenkins); (b) mixed conifer forest near Butte, MT, US, with both MPB and western spruce budworm (*Choristoneura occidentalis* Freeman) mortality distributed across the hillside (photo by M.J. Jenkins); (c) single-tree experimental fires conducted by Rocca (2010) in Rocky Mountain National Park, CO, US (photo by B. Cotton, Colorado State University); (d) Carrott Lake experimental fire in British Columbia, Canada, August 2006 (photo by D. Hicks, British Columbia Wildfire Management Branch); (e) Archer Lake experimental fire (Plot 7) in north-eastern Alberta, Canada, May 2009 (photo courtesy of FPInnovations and Alberta Environment and Sustainable Resource Development); (f) Valley Road Fire on the SNRA, 8 September 2005 (photo by A. Norman, USDA Forest Service); and (g) Tatuk Lake Fire in British Columbia, Canada, 23 June 2004 (photo courtesy of British Columbia Forests, Lands and Natural Resources Operations).

safety implications of recent MPB-related tree mortality on fire behaviour and have circulated safety bulletins to address potential concerns (e.g. National Interagency Fire Center, 2011). Given the importance and timeliness of this topic, it is imperative that additional clarity be brought to bear on the subject based on new research and the reinterpretation of important concepts and assumptions regarding wildland fire behaviour modelling.

This paper constitutes a digest and critical analysis of the pertinent literature dealing with crown fire potential in lodgepole pine forests recently attacked by the MPB. A discussion of the important

Downloaded from http://forestry.oxfordjournals.org/ by guest on February 26, 2014

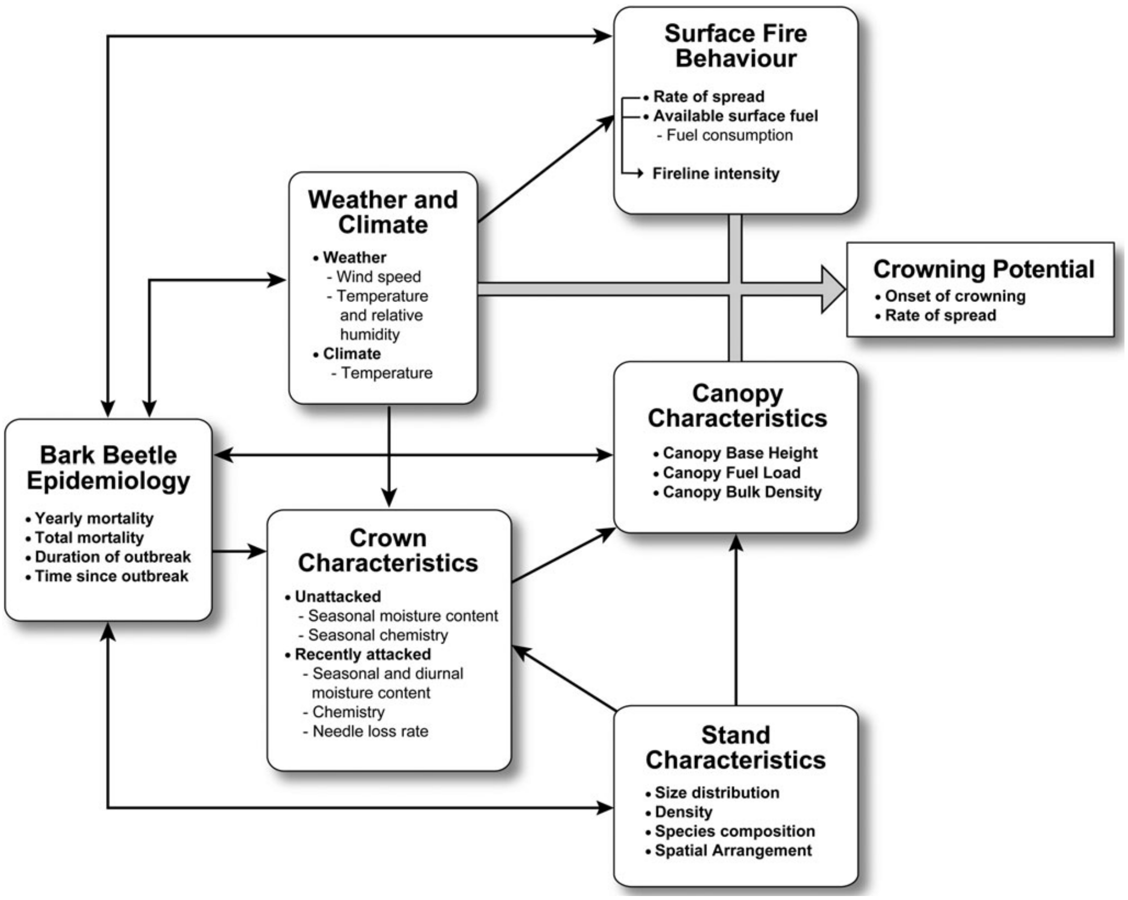

Figure 2 Flow diagram illustrating the primary characteristics and inter-relationships among the elements contributing to crown fire potential in MPB-affected lodgepole pine forests.

surface, crown and canopy fuel characteristics altered by MPB attack that may affect crown fire potential during the red stage are presented (Figure 2) along with the results of fire behaviour simulation studies focussing on crown fire initiation and spread conducted using both operational and physics-based fire behaviour models. The limitations of simulation-based studies are described in detail and the complications associated with variable tree mortality through time are characterized in terms of predicted fire behaviour. In addition, results from experimental fires conducted at the single tree and stand levels are reviewed as well as wildfire behaviour observations made by firefighters and fire managers in recently attacked stands. We conclude with a discussion of future research needed to improve the robustness of crown fire assessments in lodgepole pine forests recently attacked by the MPB.

MPB effects on surface fuels

The amount and distribution of surface fuel and its effect on fireline intensity has important implications on the development and spread of crown fires (Van Wagner, 1977). Therefore, it is important that we highlight the relevant information concerning the changes to surface fuels in recently attacked lodgepole pine forests. Other more detailed discussions of the changes to surface fuels caused by MPB attack are presented elsewhere (see Jenkins *et al.*, 2008; 2014).

Unattacked lodgepole pine stands generally have sparse surface fuels, but loadings can be highly variable with mean fine fuel loads (i.e. litter and dead wood <0.64 cm in diameter) reported to be between 0.09 and 0.27 kg m^{-2} in the northern Rockies (Brown and Bevins, 1986) and 0.03–0.15 kg m^{-2} along the CO Front Range (Alexander, 1979). In recently attacked, MPB-affected lodgepole pine stands, mean fine surface fuel loads, assuming a litter bulk density of 10 kg m^{-3} (Brown, 1981), have been observed to range from 0.17 kg m^{-2} in CO (Klutsch *et al.*, 2009), 0.4 kg m^{-2} in WY (Simard *et al.*, 2011), 0.46 kg m^{-2} in CO and southern WY (Schoennagel *et al.*, 2012), 0.63 kg m^{-2} in Utah, and 0.8 kg m^{-2} in ID (Page and Jenkins, 2007a). Compared with similar unattacked stands, a significant increase in litter depth was observed in the recently attacked stands in each of the studies noted above as well as an increase in dead woody fuel <0.64 cm in diameter by Page and Jenkins (2007a). The increase in fine woody fuel is related to the decay and deterioration of attacked trees and the resulting transfer of crown foliage and small branch material to the surface. However, depending upon decay rate, fine fuel accumulation may be limited to a relatively small window within a few years of mortality (Simard *et al.*, 2012).

Downloaded from http://forestry.oxfordjournals.org/ by guest on February 26, 2014

Overstorey tree mortality not only results in a pulse of needle litter and small diameter woody fuels to the forest floor during the red stage of MPB attack, but there is also the potential for a release of shrubs and herbaceous material due to an increase in available resources caused by tree death. Most research suggests that the release of shrubs and herbs in MPB-attacked forests does not occur until the grey or post-epidemic stages of attack (Page and Jenkins, 2007a; Simard *et al.*, 2011), but depending upon the length of the outbreak, an increase in the abundance of grasses is possible and has been noted by fire managers in MPB-attacked forests in CO, US (Page *et al.*, 2013a).

MPB effects on crown and canopy fuel properties

Jenkins *et al*. (2008; 2012; 2014) and Hicke *et al*. (2012) have provided comprehensive summaries of some of the important canopy fuel properties altered by MPB-induced tree mortality. Additional research has been conducted since those reviews that directly address some of the gaps in knowledge noted by Hicke *et al*. (2012) that relates to the characteristics of foliage on MPB-attacked trees that have important implications on crown fire development and spread.

Seasonal changes in foliar moisture content and chemical composition

Quantitative descriptions of the seasonal changes in foliar moisture content (FMC, percent oven-dry weight), chemistry, and resulting flammability have been undertaken for MPB-affected tree foliage by Jolly *et al*. (2012b) in CO and MT and Page *et al*. (2012) in ID. It was found that after 12–15 months following attack, green unattacked foliage transitioned to red with a nearly 10-fold decrease in moisture content (Figure 3). Simultaneously, the chemistry of attacked tree foliage underwent substantial changes with decreases in the proportion of soluble carbohydrates and crude fat and increases in the proportion of structural compounds such as lignin and cellulose (Jolly *et al*., 2012b; Page *et al*., 2012). Terpenoids, which are highly flammable compounds and include isoprenes, monoterpenes and sesquiterpenes, were also found to be emitted at higher rates in recently attacked foliage, still present in red foliage, and correlated with needle flammability (Amin *et al*., 2012; Page *et al*., 2012). The net result of the observed changes in moisture content and chemistry was a substantial increase in flammability, specifically ignitability, due primarily to the decrease in moisture content.

Diurnal changes in FMC

In addition to the seasonal variation in moisture content of MPB-attacked tree foliage, short-term (i.e. hourly) fluctuations caused by changes in weather have recently been studied. Page *et al*. (2013b) demonstrated that the average moisture content of needles on lodgepole pine during the red stage of MPB attack was close to 10 percent and displayed little variability across ranges in air temperature and relative humidity common during dry, summertime conditions. Previous research has assumed that red needle FMC responded to changes in air temperature and relative humidity similarly to other fine dead surface fuels with a strong diurnal response (i.e. Simard *et al*., 2011; Hoffman *et al*., 2012; Schoennagel *et al*., 2012). Based on the results of a bookkeeping-system type model with fuel moisture time-lags

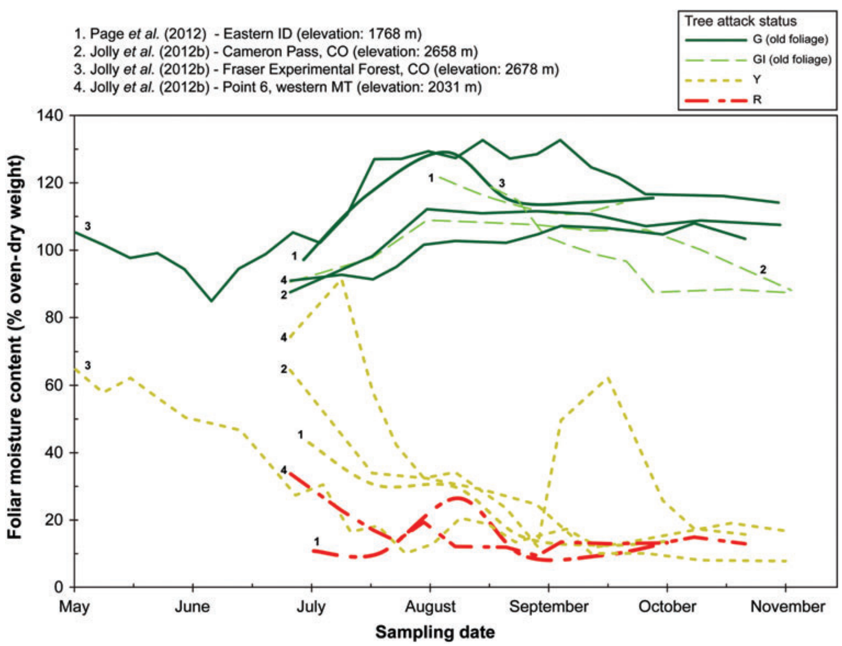

Figure 3 Combined seasonal changes in FMC measured on lodgepole pine: unattacked, green (G old foliage); recently attacked, green-infested (GI old foliage); attacked the previous year, yellow (Y); and attacked two or more years previously, red (R) by the MPB. Data are from four study sites: (1) far eastern ID, elevation 1768 m (Page *et al*., 2012), (2) Cameron Pass, north-central CO, 2658 m (Jolly *et al*., 2012b), (3) Fraser Experimental Forest, north-central CO, 2678 m (Jolly *et al*., 2012b), and (4) Point 6, western MT, 2031 m (Jolly *et al*., 2012b).

Downloaded from http://forestry.oxfordjournals.org/ by guest on February 26, 2014

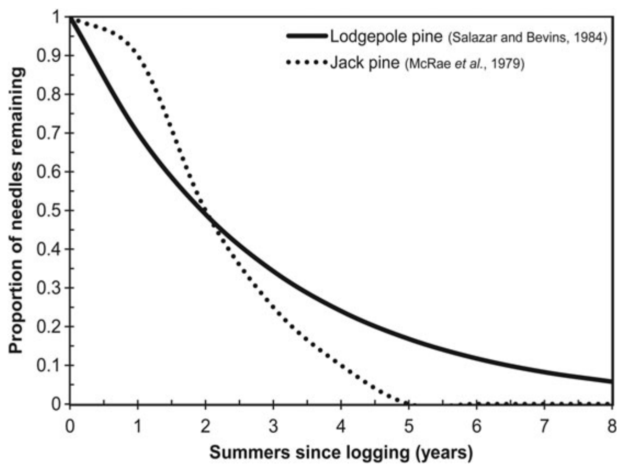

Figure 4 Needle retention over time for lodgepole pine and jack pine slash after harvest based on summaries by Salazar and Bevins (1984) and McRae *et al.* (1979).

exceeding 20 h during both adsorption and desorption phases it was suggested that longer-term (days to weeks) weather conditions have more of an effect on red needle FMC rather than short-term fluctuations in air temperature and relative humidity (Page *et al.*, 2013b).

Canopy needle retention

To our knowledge there have been no published studies which have quantified the rate of needle drop in MPB-affected lodgepole pine tree crowns even though needle retention is key to understanding the duration and severity of impact on crown fire behaviour (Simard *et al.*, 2012). Based on field guides using rough approximations, needles are thought to be retained in crowns for up to 3 years after attack (British Columbia Ministry of Forests, 1995). While published studies of needle drop rates for MPB-attacked stands are non-existent, there have been several needle retention studies undertaken in short-needled pine logging slash. Salazar and Bevins (1984) presented species-specific equations used to predict needle retention over time based on summaries of previous work. In addition, McRae *et al.* (1979) provided estimates of needle retention for jack pine logging slash (Figure 4), which is physiologically similar to lodgepole pine (Farrar, 1995). These estimates are likely on the high end of what would be expected in MPB-affected tree crowns due to the crowns constant exposure to wind but do confirm that the majority of the needles are retained for a 3–4-year period.

Changes to canopy fuel stratum characteristics

MPB-caused tree mortality usually occurs over the course of several years, which leads to heterogeneous stand canopies with individual tree crowns (Figure 1a,b) in a variety of physical and chemical conditions (Jenkins *et al.*, 2008; Jolly *et al.*, 2012b; Page *et al.*, 2012). Trees attacked in the previous year (yellow) or two or more years previously (red) occur with unattacked green tree crowns in relative proportions dependent upon the yearly and total amount of mortality, the duration of the outbreak, and the individual stand characteristics.

Most of the quantitative-based studies of MPB-related tree mortality on canopy fuel characteristics have found that the canopy bulk densities (CBD, kg m^{-3}) in recently attacked stands are lower compared with similar, unattacked stands (Klutsch *et al.*, 2011; Simard *et al.*, 2011; Schoennagel *et al.*, 2012). Even with the effects of needle drop in recently attacked red stage stands, the proportion of red foliage in the canopy can still be significant and can occur with a high proportion of attacked trees containing the majority of needles within their crowns (Figure 5). For example, during the 2004 fire season, Page and Jenkins (2007a) found that in recently attacked stands on the Sawtooth National Recreation Area (SNRA) in central ID, US, 30 percent of the total foliage in sampled stands was red and that >35 percent of those attacked trees had >50 percent of their needles present. MPB populations in the lodgepole pine stands on the SNRA were declining during the period of sampling, suggesting that a high level of needle retention is possible even at the end of an outbreak.

In addition to the changes to foliage, it has been noted that the small diameter dead twig material within the crowns of red trees also has low moisture contents, with a seasonal mean of 15 percent which was only slightly higher than the mean reported for red foliage of 13 percent (Page *et al.*, 2012). Typically, much of this twig material is not consumed during crown fires in healthy forests, but the dramatic decrease in moisture content could potentially make more of the twig material available for combustion during the active flaming phase of a crown fire, thereby adding mass to the available canopy fuel load. Therefore, the loading of canopy fuel available to crowning within red stage lodgepole pine forests is a function of both the mass of foliage within the canopy and the mass of small diameter twig material that can be consumed during crowning, which has not adequately been incorporated into any previous canopy fuel descriptions.

Crown fire initiation in recently attacked lodgepole pine forests

Most of the current published research on fire behaviour potential in recently attacked, MPB-infested lodgepole pine forests has been carried out using fire behaviour modelling systems developed in the US. Thus, the focus of the discussion will be within the context of these systems and their underlying models.

Current fire behaviour predictive models and known limitations

Crown fire initiation in conifer forests is dependent upon several characteristics of the canopy fuel layer and surface fire behaviour. The surface fire characteristic deemed most important to crown fire initiation is Byram's (1959) fireline intensity, defined as the rate of heat released from a linear segment of the fire perimeter (kW m^{-1}), calculated as the product of the low heat of combustion (kJ kg^{-1}), the fuel consumed in the active flame front (kg m^{-2}), and the linear rate of fire spread (m s^{-1}) (Alexander, 1982). Fireline intensity takes into account the combined physical characteristics of the fuel complex and the effects of long- and short-term weather on fuel dryness, wind speed and slope steepness on surface fire behaviour (Alexander and Cruz, 2012). All of the fire behaviour modelling systems developed in the US use Rothermel's (1972) surface fire spread model to estimate fireline intensity,

Downloaded from http://forestry.oxfordjournals.org/ by guest on February 26, 2014

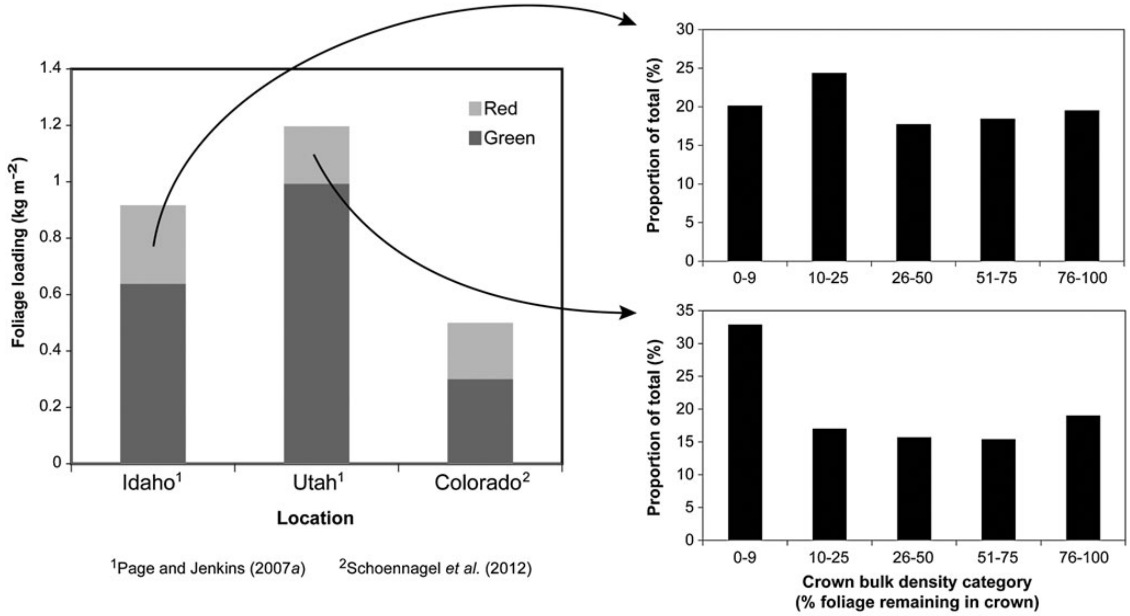

Figure 5 Summary of red and green foliage fuel loads in recently attacked MPB-infested lodgepole pine stands sampled in Utah on the Wasatch-Cache National Forest and on the SNRA in ID by Page and Jenkins (2007a), and in CO by Schoennagel *et al.* (2012). The proportion of attacked trees within crown bulk density categories sampled by Page and Jenkins (2007a) is also shown for the stands in Utah and ID.

which has been shown to under-predict the fire spread rate and fireline intensity in surface fuel beds composed of needle litter (Cruz and Alexander, 2010). The under-prediction bias is related to the under-estimation of flame front residence time using Anderson's (1969) model combined with Rothermel's (1972) reaction intensity and the general under-prediction of rate of fire spread in timber dominated fuel types, including lodgepole pine (Lawson, 1972), which is thought to be due to the model's sensitivity to the compactness of horizontally oriented fuel beds (Cruz and Fernandes, 2008; Cruz and Alexander, 2010).

Van Wagner (1977) developed a simple model to determine the critical fireline intensity value needed to initiate crowning in a conifer forest based on two canopy fuel properties, namely canopy base height (CBH) and FMC. Embedded within Van Wagner's (1977) simple model is an empirical constant of 'complex dimensions' as determined by a single-experimental fire conducted in a red pine (*P. resinosa* Aiton) plantation with a FMC of 100 percent and a CBH of 6.0 m (Alexander and Cruz, 2011). When the relationship is linked with Rothermel's (1972) surface fire spread model in the context of the US fire behaviour modelling systems, an under-prediction bias in the onset of crowning has been identified (Cruz and Alexander, 2010).

Interpretation and limitations of current research

Due to the limitations associated with the current US fire behaviour modelling systems, in terms of accurately quantifying crown fire initiation, some researchers have relied upon qualitative assessments based on logical reasoning and the observed and predicted changes to important surface, crown, and canopy fuels measured in the field as described in the previous sections. For example, the well-established relationship between moisture content and leaf flammability (e.g. Pompe and Vines, 1966; Dimitrakopoulos and Papaioannou, 2001) has been used to suggest that the presence of 'dead and red' trees might more easily facilitate the transition of a surface fire to a crown fire, especially where the combination of CBH and/or surface fireline intensity would otherwise limit crown fire initiation (Schmid and Amman, 1992; Page and Jenkins, 2007b; Jenkins *et al.*, 2008). These predictions were based on assumed decreases in moisture content during the red stage of MPB attack, the significant proportion of canopy fuel composed of the dead or 'red' foliage, and the increase in surface fire behaviour predicted to occur from higher fine fuel loads and increases in within-stand wind speeds (Page and Jenkins, 2007b; Jolly *et al.*, 2012b; Page *et al.*, 2012).

Even with the known limitations of current fire behaviour models, some researchers have still attempted to quantify crown fire initiation in recently attacked stands (e.g. Simard *et al.*, 2011; Schoennagel *et al.*, 2012). Using the NEXUS fire behaviour modelling system (Scott and Reinhardt, 2001), it was suggested that that Torching Index (6.1-m open wind speed required to initiate crowning) exceeded 500 km h^{-1} in both unattacked and recently attacked lodgepole pine stands in WY, US, with a mean CBH of 3.1 m (Simard *et al.*, 2011). Clearly those values are unrealistic as crown fires are regularly known to occur in similar forests under much lower wind speeds (e.g. Thomas, 1991; Renkin and Despain, 1992) and reflect the problems associated with current operational fire behaviour models. Using the BehavePlus fire behaviour modelling system (Andrews *et al.*, 2008), another attempt at simulating crown fire initiation in recently attacked stands (Schoennagel *et al.*, 2012) found that the critical surface fireline intensity needed to initiate crowning was significantly lower in red stage stands than green or unattacked stands, however evidence of an under-prediction bias was still present with 6.1-m open wind speeds in

Downloaded from http://forestry.oxfordjournals.org/ by guest on February 26, 2014

excess of 50 km h^{-1} needed to initiate crowning under very dry fuel conditions and with a mean canopy base height of ~4 m.

Despite the widespread use of Van Wagner's (1977) relationship for the onset of crowning, its empirical proportionality constant is in fact specific to the set of fire environment conditions associated with an experimental fire in a red pine plantation from which it was derived (Alexander and Cruz, 2011; Jenkins *et al.*, 2012). Thus, when applying the relationship to MPB-attacked lodgepole pine stands the empirical constant undoubtedly needs to be readjusted using experimental fire observations if, for example, it deviates widely from the original derivation (Cruz and Alexander, 2010). Such observations are difficult to come by as most have been qualitative in nature or were not set up to quantify the critical point of transition. For example, in MPB-attacked lodgepole pine forests in ID, MT and OR, wildland fire personnel have observed, but not quantitatively documented, more prolific spotting, an increased tendency for surface fires to transition to crown fires, and increases in resistance to control (Church *et al.*, 2011; Stiger and Infanger, 2011).

However, in more quantitatively based field observations related to the potential for crown fire initiation, Rocca (2010) reported on individual tree torching tests involving 17 unattacked and recently attacked trees in Rocky Mountain National Park in north-central CO using a propane torch applied to the base of tree crowns (Figure 1c). The red trees were tested with four categories: mixed with green needles (100 percent needles remaining) and 40–59, 60–79 and 80–100 percent needles remaining. They found that crown flammability was higher in red trees with successful crown ignition in trees having >60 percent of their needles remaining and that there was no ignition in green tree crowns or red crowns having <60 percent of their needles remaining. They concluded that there was an increase in fire risk immediately following an outbreak but that it may be short-lived due to needle drop.

Given the current limitations of operational fire behaviour models and limited observations in the field, it is critical that more quantitative field-based assessments of crown fire initiation be attempted. The evidence to-date still clearly suggests that crown fires are more likely to initiate in recently attacked lodgepole pine forests during the red stage compared with unattacked forests but we will be unable to accurately define the point of transition until either new models are developed or a proportionality constant applicable to dead canopy fuels is defined for Van Wagner's (1977) model for crown fire initiation. The observations should focus on the range of CBHs and surface fire intensities where an effect is most likely to be detected. When Van Wagner's (1977) model for crown fire initiation is applied to normal and worst-case scenarios of FMC, the range of fireline intensities and CBHs where MPB mortality may have the most effect on crown fire initiation can be displayed graphically (Figure 6). According to the predictions from Van Wagner's (1977) model, stands with low CBHs (especially <2.0 m) are susceptible to the onset of crowning regardless of the level of MPB-related tree mortality, while stands with relatively high CBHs are more vulnerable to changes in crown fire initiation due to the presence of recent MPB-related tree mortality. Thus, future experimental fires and/or wildfire observations looking to detect an effect of recent mortality on crown fire initiation should focus on stands with relatively high canopy base heights (i.e. >4–6 m) and weather conditions that produce surface fireline intensities < 5000 kW m^{-1} for a given set of surface fuel conditions.

Crown fire spread in recently attacked lodgepole pine forests

Models that have been used to-date for simulating crown fire spread rate, fuel consumption, and intensity in lodgepole pine forests recently attacked by the MPB can be considered as reflecting the 'two solitudes' to forest fire behaviour research as described by Van Wagner (1971). The empirical or semi-empirical approach is based on the analysis of observational data gathered from the laboratory or the field (i.e. experimental and/or wildfires) to produce either statistical models incorporating the significant drivers of fire propagation, supplemented by simple theory (e.g. Forestry Canada Fire Danger Group, 1992), or fit into a framework based on physical theory (e.g. Rothermel, 1972). The physics-based approach to fire behaviour model development makes use of advances in computational power to solve the fundamental equations of mass, momentum and energy for spreading wildland fires (Sullivan, 2009).

Current fire behaviour models and known limitations

The empirically-based models used in the US that have been most often used to quantify crown fire rate of spread in MPB-attacked forests are based on the active crown fire propagation threshold described by Van Wagner (1977) and the active crown fire rate of spread model as described by Rothermel (1991). Crown fire propagation is normally classified on the basis of the dependence upon the surface fire, i.e. either passive or active (Van Wagner, 1977). A passive crown fire is expected to occur when CBH and FMC are sufficiently low for a surface fire of given intensity to ignite the foliage but the final spread rate is below the minimum threshold needed to sustain active crowning for a given amount of fuel in the canopy layer. Van Wagner (1977) proposed a simple model for determining this minimum threshold for active crowning based upon the amount of available canopy fuel divided by the depth of the canopy layer (i.e. the CBD), and the minimum mass flow rate needed to sustain active crowning. Van Wagner (1977) assumed a minimum mass flow rate of 0.05 kg m^{-2} s^{-1} based on fire behaviour observations in red pine plantations with FMC values between 95 and 135 percent. An active crown fire is expected to occur when both the surface fireline intensity is above the critical threshold needed to initiate crowning and CBD is high enough to sustain crowning for a given rate of fire spread. In live and healthy conifer stands, a CBD above 0.1 kg m^{-3} is generally considered as the minimum for active crown fire spread (Agee, 1996; Cruz *et al.*, 2005; Alexander and Cruz, 2011).

In US fire behaviour modelling systems, once the critical intensity needed for crown fire initiation has been met, Van Wagner's (1977) active crown fire propagation threshold is evaluated to determine the type of crown fire, (i.e. either passive or active). If the minimum conditions of rate of spread and CBD have been met then Rothermel's (1991) model is used to predict the active crown fire rate of spread. A significant under-prediction bias has been detected on the basis of comparing model predictions to observations of experimental and wildfires in conifer forests (Cruz *et al.*, 2005; Alexander and Cruz, 2006; Cruz and Alexander, 2010). Possible reasons for the bias include the dependence of the model on the fire behaviour fuel model 10 (Anderson, 1982), the use of only seven fires to develop the statistical correlation, and the model's low sensitivity to changes in wind speed (Cruz and Alexander, 2010).

Downloaded from http://forestry.oxfordjournals.org/ by guest on February 26, 2014

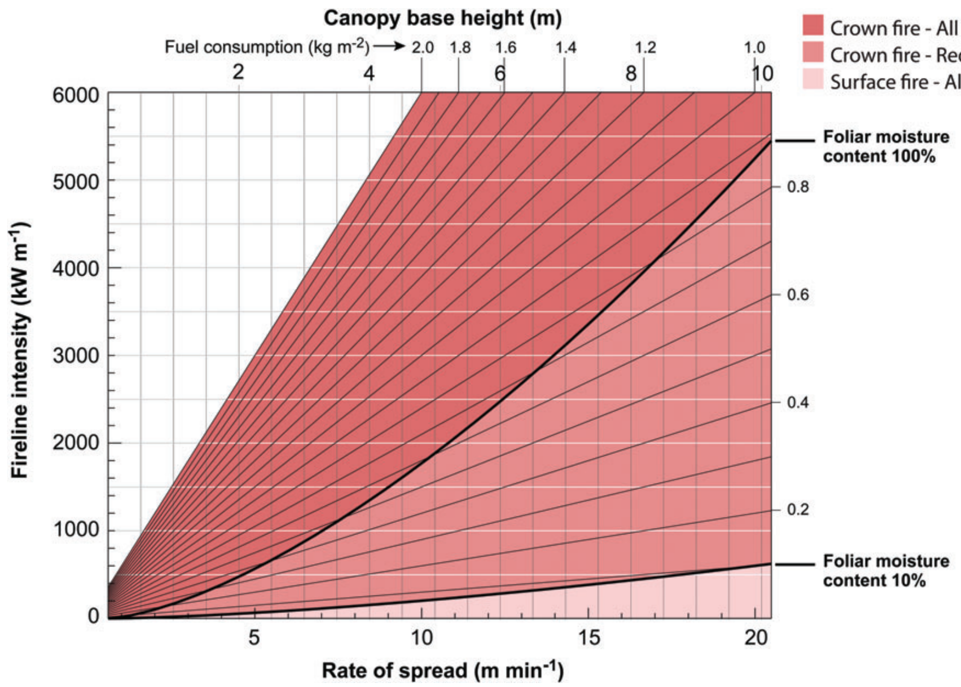

Figure 6 Graphical representation of Van Wagner's (1977) crown fire initiation relationship with demarcation of the critical intensities obtained at FMCs of 10% and 100% and canopy base heights between 0 and 10 m. The FMC of 100% represents the common value assumed to represent live, healthy conifer stands during the fire season (Keyes, 2006) and the 10% represents a low FMC expected in recently attacked MPB-affected stands with near complete mortality (Page *et al.*, 2013b). The three designated zones correspond to the range of fireline intensities and canopy base heights where crown fire initiation is expected within both healthy, unattacked stands and recently attacked stands (Crown fire – All), where crown fire initiation may occur in recently attacked stands but not in unattacked stands (Crown fire – Red), and where crown fire initiation is unlikely (Surface fire – All). Fireline intensities were calculated as the product of rate of spread and fuel consumption as per Byram (1959), assuming a net heat of combustion of 18 000 kJ kg^{-1} (Stocks *et al.*, 2004b). The fireline intensity can be obtained by noting the intersection between the appropriate rate of spread and fuel consumption lines and reading the *y*-axis. **Sample calculation:** given a fine surface fuel load of 0.6 kg m^{-2}, a rate of spread of 10 m min^{-1}, and a canopy base height of 6 m, the estimated fireline intensity would be noted by reading the *y*-axis where the appropriate fuel consumption and rate of spread lines meet, which in this case would be ~1800 kW m^{-1}. Then to determine the possible influence of recent tree mortality on crown fire initiation, note where the 1800 kW m^{-1} and 6 m canopy base height (located on top of graph) lines intersect. In this case they intersect in the Crown fire – Red zone, which indicates that conditions are such that a transition to crowning caused by the presence of recently killed trees is possible when such a transition would otherwise be unlikely if the stand contained only live and healthy foliage.

The primary physics-based fire behaviour model that has been applied in MPB-attacked forests is the Wildland–urban interface Fire Dynamics Simulator (WFDS) (Mell *et al.*, 2007). Additionally, FIRETEC (Linn *et al.*, 2002), another physics-based fire behaviour model, has been used to simulate fire spread in pinyon–juniper (*Pinus edulis*–*Juniperus* spp.) woodlands affected by the pinyon ips (*Ips confuses* LeConte) (Linn *et al.*, 2013). Both models attempt to simulate interactions between the atmosphere, fuel and fire using three-dimensional, time-dependent grids where the physical mechanisms of heat and mass transfer are solved. The popularity of the models among fire researchers appears to be increasing because of their perceived ability to simulate fire spread through non-homogenous fuel complexes. This is despite the fact that very little has been done to validate the outputs, particularly in conifer forest stands where surface fuels are dominated by litter and dead woody material, and where a distinct gap exists between surface and canopy fuels. This lack of evaluation with respect to model performance in conifer forests brings into question the accuracy of the outputs obtained and the robustness of the resulting conclusions (Alexander and Cruz, 2013a).

Interpretation and limitations of current research

There is currently widespread agreement among researchers that once the majority of the needles have dropped from the crowns and the stand has entered the grey stage of MPB attack, active crown fire potential substantially decreases (Jenkins *et al.*, 2008; Hicke *et al.*, 2012), although not necessarily fire behaviour potential in general (Jenkins *et al.*, 2012), based on observations of several well-documented wildfires (Stiger and Infanger, 2011; D.T. Hicks, British Columbia Forests, Lands and Natural Resources Operations, personal communication, 2013). There is, however, disagreement regarding the assessment of active crown fire spread during the red stage, as both highly flammable foliage is present but is also being lost from the canopy fuel layer as the time since the outbreak began increases. Nevertheless, this disagreement should not underestimate the importance and likelihood of high-intensity, passive crown fires and profuse, short- and medium-range spotting throughout the period of needle fall in red stage forests (Jenkins *et al.*, 2012; Page *et al.*, 2013a).

The mixture of crowns in various conditions or attack stages, the gradual loss of foliage, and the site-specific characteristics of both the affected stand and adjacent stands results in highly complex

Downloaded from http://forestry.oxfordjournals.org/ by guest on February 26, 2014

spatial arrangements that may have important but as yet unknown implications on crown fire spread. For example, the high ignitability of red trees increases the likelihood of torching, which when considered with their spatial relationship to other trees may facilitate the ignition of adjacent tree crowns. Bark beetle-caused tree mortality has been shown to display clustering (e.g. Rossi *et al*., 2009), especially during the early stages of an outbreak when large trees are preferentially attacked (Cole and Amman, 1969). The transitions from unattacked to red attack patches or stands, depending upon the scale of interest, are especially important as a shift to crowning can, at the very minimum, double the rate of fire spread and fireline intensity (Alexander and Cruz, 2011). The often dramatic and unanticipated changes in fire behaviour that occur as a fire burns from one fuel type to another has been recognized as a key element affecting firefighter safety (Bachop, 1998; Bishop, 2007). Thus, complex interactions among beetle epidemiology such as the yearly, total amount and distribution of mortality and foliage flammability exist.

The two primary studies that have attempted to quantify crown fire spread in recently attacked, MPB-infested lodgepole pine stands using US fire behaviour modelling systems came to opposite conclusions. In red stage stands in north-western WY, US, there was a predicted decrease in active crown fire potential due to the loss of canopy fuel (Simard *et al*., 2011) while in similar stands in CO, US, there was an increase in active crown fire potential (Schoennagel *et al*., 2012). Both conclusions are suspect given the limitations of the underlying operational fire behaviour models used in these studies. It is unknown whether Van Wagner's (1977) criteria for active crowning and its assumed minimum mass flow rate of 0.05 kg m^{-2} s^{-1} based on fire behaviour observations in red pine plantations containing live foliage is pertinent to stands where the canopy contains significant amounts of dead foliage. Van Wagner's (1977) criterion was shown to be reliable in defining the transition from passive to active crowning in live conifer stands (Cruz *et al*., 2005; Cruz and Alexander, 2010), but it has yet to be evaluated in stands containing significant amounts of dead foliage.

In an attempt to incorporate the potentially important contribution of the dead foliage on recently attacked trees to crown fire rate of spread, Moran and Cochrane (2012) suggested the use of Van Wagner's (1989) foliar moisture effect (FME) function. Van Wagner (1989) proposed that crown fire rate of spread in live and healthy conifer forest stands is affected by FMC and in turn derived a theoretical function for adjusting the crown fire spread rate based on the average FMC of 97 percent for the experimental crown fires and crowning wildfires used in the development of the Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group, 1992; Taylor *et al*., 1997). Based on the Simard *et al*. (2011) data, Moran and Cochrane (2012) used the function to demonstrate an under-prediction bias in active crown fire spread rate by a factor of $\sim$2, assuming a FMC of 63 percent. Alexander and Cruz (2013b) discussed in considerable depth the derivation and application of Van Wagner's (1989) FME function for adjusting crown fire rate of spread. They demonstrated that the function is unrealistically strong at the low FMCs found in the red stage of MPB-attack, showing that there would be a 10-fold increase in the predicted crown fire spread rate at a FMC of 5 percent. It is worth noting that Moran and Cochrane's (2012) use of the FME suggests that a drop in CBD and subsequent rise in the critical rate of spread needed for active crowning can be offset by a corresponding increase in the crown fire rate of spread. This however does not imply that the critical mass flow rate is less in stands with low FMC values as the flow rate is in fact independent of moisture content (Thomas, 1967; Van Wagner, 1977). Rather, the net effect of a low FMC would be either no change or an increase in the fire's final rate of spread once the transition to crowning occurs. Indeed, if a FME does exist it could be on the order of two to three times greater than the no-tree mortality case (Alexander and Cruz, 2013b).

The results of crown fire spread assessments using WFDS in MPB-attacked lodgepole pine stands during the red stage have been closer to expectations but the reliability of the results are still unknown. WFDS was used to examine the influence of recent MPB mortality on simulated fire behaviour in lodgepole pine stands using tree data collected from field sites in OR and ID, US (Hoffman *et al*., 2012; 2013). Hoffman *et al*. (2012) simulated surface fireline intensity using a constant rate of spread of 6.0 m min^{-1}, with a flame front residence time of 25 s, a 6.1-m open wind speed of 7.2 km h^{-1}, and a surface fireline intensity of 625 kW m^{-1}. They found that as tree mortality increased there were increases in crown fuel consumption, fireline intensity, and that pre-outbreak stand structure was an important variable affecting the fireline intensity of crown fires. However, no evaluation was offered of the ability for WFDS to accurately predict either crown fuel consumption or fireline intensity of crown fires in conifer forest stands. Furthermore, the setting of all the relevant surface fire behaviour characteristics as constants severely limited the usefulness of the stated purpose of a physics-based model like WFDS, which should be able to predict the full range of fire behaviour.

Hoffman *et al*. (2013) also used WFDS to assess crown fuel consumption and a crown fire's fireline intensity in recently attacked MPB-infested stands across three different surface fireline intensity levels. The simulated fireline intensities ranged from 313 to 1250 kW m^{-1}, but the flame front residence time, rate of fire spread, and 6.1-m open wind speed were held constant. The results suggested that higher levels of tree mortality increased crown fuel consumption and the fireline intensity of crown fires, and that the increase was greatest under moderate surface fireline intensity values. Again, no empirical evidence of WFDS's ability to predict crown fuel consumption or intensity of crown fires in conifer forest stands in general was offered. While these results fit with expectations described by previous researchers (e.g. Jenkins *et al*., 2008), there are underlying concerns as to the reliability of the projections due to the use of an un-validated model and the assumption that the MPB-killed red trees retained all of their foliage at the time of the fire, when in fact, such a situation may be relatively rare (Simard *et al*., 2012).

In spite of concerns about lack of evaluation of physics-based models and their use to simulate fire spread in complex fuel conditions affected by bark beetle outbreaks (Alexander and Cruz, 2013a), they continue to be applied in similar situations. Linn *et al*. (2013), for example, used FIRETEC to compare fire spread rates in pinyon–juniper woodlands following attack by the pinyon ips by simulating fire spread in unattacked, green or living stands, stands in which the moisture content of pinyon needles were lowered to 15 percent, and stands where the needles on the attacked pinyon trees were transferred to the ground. It was found that fire spread was $\sim$2 times faster in the simulation containing tree crowns with low moisture contents compared with

Downloaded from http://forestry.oxfordjournals.org/ by guest on February 26, 2014

the green stands and that fire propagation was also enhanced where the needles were transferred to the ground due to increased wind penetration. Although no formal evaluation of the outputs was given, observations and data do exist for green stands (Hester, 1952; Bruner and Klebenow, 1979) to evaluate the model's performance in a semi-quantitative sense (e.g. wind speed threshold in a discontinuous fuel type).

Field observations of fire behaviour

As a result of the controversial nature of some of the conclusions drawn from the simulation-based assessments of crown fire potential in MPB-attacked forests, it is important to consider the fire behaviour observations and measurements made by wildland fire research and fire operations personnel in the field. Comparisons of the observed rates of spread with predictions made using the appropriate operational fire behaviour model, either the FBP System for Canadian wildland fires or the US fire behaviour modelling systems, are also mentioned where appropriate.

Experimental fires

The experimental fires conducted in spruce budworm-killed (*Choristoneura fumiferana* Clemens) balsam fir (*Abies balsamea* (L.) Mill.) forests in north-central Ontario, Canada, by Stocks (1987) constitute the only published field study of fire behaviour in a standing, dead conifer forest fuel complex. The results, which formed the basis, in part, for the M-3 (dead balsam fir mixedwood – leafless) and M-4 (dead balsam fir mixedwood – green) FBP System fuel types, provide a useful comparison of fire behaviour potential in insect-affected stands and may provide additional insights into potential fire behaviour in MPB-affected stands. The experimental fires conducted in the spring, soon after nearly complete tree mortality, displayed extensive crowning, high spread rates and prolific, short-range spotting, even under relatively mild burning conditions. As a wildland fire behaviour phenomena, spotting is a process not presently accounted for in either WFDS or FIRETEC but is indirectly incorporated into Rothermel's (1991) active crown fire rate of spread model and the FBP system.

Stocks (1987) showed that fire behaviour potential in the affected balsam fir stands peaked 5–8 years after mortality due to a combination of crown breakage and windthrow, and gradually decreased as surface fuels decomposed and understorey shrub cover increased. Using fuel type M-3 as a surrogate for recently attacked-MPB stands and the FBP System fuel type C-3 (mature jack or lodgepole pine) to represent the live and healthy forest stand, Alexander and Cruz (2013b) computed the continuous ratio in the predicted spread rates between the two, finding that the former fuel type would have a rate of fire spread 2.5–3.6 times greater.

In August 2006, two experimental fires were conducted at the Carrott Lake experimental fire study area in north-central British Columbia, Canada (Table 1), in a mature lodgepole pine stand attacked by the MPB mostly during the period from 2002 to 2004 (Figure 1d). The goal of the project was to quantitatively assess the impact of MPB-related tree mortality on fire behaviour (Lavoie and Taylor, 2007). The two plots burned were entering the grey stage of MPB attack with most of the successfully attacked lodgepole pine trees having lost the majority of their needles (Table 1). Observed fire behaviour within the plots was primarily a surface fire with observed head fire spread rates similar to predictions made using the FBP System C-3 fuel type, which were $\sim$1.2 m min^{-1} for Plot 1 and $\sim$2.4 m min^{-1} for Plot 3 (Table 1). Due to the rapidly changing nature of the fuel complex and the difficulty of trying to burn during prescribed fire weather conditions, no further burning was done in any plots while they were in the red stage.

In an attempt to better understand the impacts of recent MPB-related tree mortality on fire behaviour, a series of experimental fires were conducted near Archer Lake in northeast Alberta, Canada, in July 2008 and July 2009 (Schroeder and Mooney, 2009, 2012). MPB attack was simulated by girdling 90 percent of the overstorey jack pine trees in 2007 on plots 0.12–4 ha in size. Fires were simultaneously ignited in simulated green-attack and red stage stands (Figure 1e). The results of the green-attack experimental fires in 2008 were inconclusive due to the ignition techniques used and the observation of rapid crown fire development in both the control and girdled plots. The results of the 2009 fires indicated little to no difference in spread rates between the control and girdled plots, greater crown involvement in the girdled stands during the passive crown fire phase due to the low FMCs, and no difference in the fire danger rating threshold for crown involvement (Table 1). Comparisons of the spread rates with the predictions from the FBP System indicated that spread rates were higher than predicted using the C-3 FBP System fuel type, but under the less severe fire weather conditions, the C-4 (immature jack or lodgepole pine) fuel type more closely matched observations for both the control and girdled plots (see Schroeder and Mooney, 2012).

Schroeder and Mooney (2012) suggested that the low crown bulk density of the red simulated attack trees decreased their effect on crown fire development in the attacked stands. The implications of these results on potential fire behaviour in MPB-attacked lodgepole pine stands are difficult to interpret due to limitations of the experimental fire design. Rarely in naturally attacked lodgepole pine stands would 90 percent of the tree mortality occur all within 1 year. It is also unknown how the rate of needle moisture loss and needle drop in girdled trees compares to MPB-attacked trees. In naturally attacked stands, tree mortality occurs over a period of several years producing stands with heterogeneous crown conditions resulting in more available crown fuel over a longer period of time than if all the tree mortality occurred during 1 year.

Wildfires

Armitage (2004) reported on fire behaviour observations obtained from wildfires that burned through recently attacked lodgepole pine stands during the summer of 2004 in British Columbia (Figure 1g and Table 1). He noted that fire behaviour was more severe in recently attacked stands compared with unattacked stands, with increased probabilities of ignition, a lower surface fire intensity threshold to initiate crowning, and greater crown fuel consumption. Long distance spotting was also observed in affected stands under low wind conditions and red tree crowns proved to be receptive to spot fire development, which hampered fire suppression operations. Recommendations were that firefighter training should note the possibility of extreme fire behaviour and increased suppression difficulties in recently attacked stands even under less than extreme weather conditions and that bull-dozer line width should be increased in order to prevent radiant heat from igniting red crowns on the opposite side of the fireline.

Downloaded from http://forestry.oxfordjournals.org/ by guest on February 26, 2014

Table 1 Summary of the weather conditions, fire behaviour, and fire danger ratings associated with the experimental fires and wildfires that burned through recently attacked mountain pine beetle (MPB)-infested lodgepole pine stands or simulated cases (i.e. Archer Lake)

Type of observed or measured fire – name of fire	Total mortality (%)[2]	Type of fire[3]	Head fire spread rate (m min^{-1})	Air temperature (°C)	Relative humidity (%)	10-m Open wind speed (km h^{-1})	NFDRS ERC		FWI System	
							Obs.	97th	DMC	DC
Experimental fires										
Carrott Lake, BC – Plot 1	86	Surface	~1–3	20	39	10	–	–	43	472
Carrott Lake, BC – Plot 3	84	Surface	~2–6	21	34	9	–	–	74	549
Archer Lake, AB – Burn 1a	0	Surface	3.0	22	45	8	–	–	36	317
Archer Lake, AB – Burn 1b	90	Surface	3.0	22	45	8	–	–	36	317
Archer Lake, AB – Burn 3a	0	Intermittent crown	4.0	24	35	12	–	–	36	317
Archer Lake, AB – Burn 3b	90	Intermittent crown	4.0	24	35	12	–	–	36	317
Archer Lake, AB – Burn 4a	0	Surface	3.0	22	35	6	–	–	40	324
Archer Lake, AB – Burn 4b	90	Surface	3.0	22	35	6	–	–	40	324
Archer Lake, AB – Burn 5a	0	Surface	3.1	23	31	5	–	–	40	324
Archer Lake, AB – Burn 5b	90	Surface	2.6	23	31	5	–	–	40	324
Archer Lake, AB – Burn 6a	0	Intermittent crown	8.8	21	37	10	–	–	43	332
Archer Lake, AB – Burn 6b	90	Intermittent crown	6.5	21	37	10	–	–	43	332
Archer Lake, AB – Burn 7a	0	Intermittent crown	3.2	22	37	10	–	–	43	332
Archer Lake, AB – Burn 7b	90	Continuous crown	7.6	22	37	10	–	–	43	332
Wildfires										
Kenney Dam, BC[4] (26 June 2004)	nr	Continuous crown	nr	28	30	10	–	–	58	348
Tatuk Lake, BC[4] (23 June 2004)	nr	Continuous crown	nr	20	64	6	–	–	45	324
Hay Lake, BC[4] (18 August, 2004)	nr	Continuous crown	nr	28	37	6–7	–	–	nr	nr
Valley Road, ID (4 September 2005)	>50	Active crown	>20	28	<15	>46	97	88	–	–
Salt, ID (29 August 2011)	30–70	Active crown	23–27	17–18	25–28	33–36[5]	80	84	–	–

[1]The observed (Obs.) and 97th percentile energy release component (ERC) of the National Fire Danger Rating System (Deeming *et al*., 1977) and the Duff Moisture Code (DMC) and Drought Code (DC) components of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner, 1987) are displayed for each fire according to country of origin, either US or Canada. The 6.1 m open wind speeds for the Valley Road and Salt wildfires were adjusted to 10-m height based on the 1.15 adjustment factor suggested by Lawson and Armitage (2008). Archer Lake plots that were missing observed rates of spread were omitted for control plots (a) and simulated attack plots (b).
[2]Reported total stand mortality; Carrott Lake plots 1 and 3 had ~1% and 7%, respectively, of the dead trees with >50% of their needles remaining within the crown at the time of burning. The Archer Lake plots were noted to have dropped at least 25% of their needles at the time of burning; nr is not reported.
[3]Intermittent crown fire is synonymous with passive crown fire and continuous crown fire is synonymous with active crown fire.
[4]Wildfires reported by Armitage (2004).
[5]Reported from a portable weather station ~9 km northeast and 162 m higher in elevation than the fire.

Downloaded from http://forestry.oxfordjournals.org/ by guest on February 26, 2014

The 2005 Valley Road Fire in the SNRA in central ID, US (Table 1), burned through MPB-attacked lodgepole pine stands that contained significant amounts of red foliage, but were entering the grey stage of MPB attack (Figure 1f). The fire started on 3 September and made major runs in MPB-attacked lodgepole pine stands on the fourth with reported 6.1 m-open wind speeds in excess of 40 km h^{-1} and near record dryness with 1000-h timelag fuel moistures (Deeming *et al*., 1977) of 7 percent (Table 1). Intense crown fire behaviour coupled with long range spotting was observed in all lodgepole pine stands regardless of the level of tree mortality during the peak burning period in mid-to-late-afternoon. Due to the critical fire weather conditions at the time, differences in fire behaviour caused by the MPB-related tree mortality were difficult to detect (A. Norman, USDA Forest Service, personal communication, 2012). Comparison of the observed spread rate during the major runs of the Valley Road Fire with the predictions made by Simard *et al*. (2011) under their 'very dry' fuel moisture scenario, assuming a 6.1-m open wind speed of 40 km h^{-1}, indicates an under-prediction, with a predicted head fire spread rate of <1.5 m min^{-1} compared with observed fire spread rates in excess of 20 m min^{-1}.

Wildfires on the Salmon-Challis National Forest in central ID, US, during the 2011 fire season that were a part of the Saddle Complex, burned through recently attacked lodgepole pine stands in both the red and grey stages. In particular, the Salt Fire burned through recently attacked MPB-affected stands with between 30 and 70 percent tree mortality. On August 29, extreme fire behaviour was observed as an active crown fire entrapped a dozer operator and transport driver (Church *et al*., 2011) with an observed head fire spread rate estimated at 23–27 m min^{-1} (Table 1). Church *et al*. (2011) reported in the fire behaviour forecast for the day, that the maximum predicted spread rate was ~7 m min^{-1} based on the TU4 (dwarf conifer with understorey) surface fuel model of Scott and Burgan (2005) utilized by the fire behaviour analyst assigned to the incident. The maximum observed spread rate was ~3.3 times higher than the predicted maximum spread rate for the day. Comparison of the maximum observed head fire spread rate with predictions made using the Rothermel (1991) active crown fire spread rate model indicates slight under-prediction with a predicted spread rate of 17 m min^{-1} assuming a fine fuel moisture of 7 percent and a slope of 23 percent. The Cruz *et al*. (2005) active crown fire spread model predicts an active crown fire spread rate between 53 and 58 m min^{-1}, assuming a CBD of between 0.1 and 0.16 kg m^{-3}, which roughly corresponds to similar lodgepole pine stands in ID, US, with tree heights of ~15 m (Page and Jenkins, 2007a).

A quantitative-based assessment of fire behaviour in MPB-affected lodgepole pine forests in British Columbia has recently been undertaken by Perrakis *et al*. (2012). Using photographs obtained from the provincial air attack program for free-burning wildfires during the years 2006–2010, an analysis of head fire rates of spread was attempted based on visual interpretation of the photographs taken by air attack officers and weather data gathered from the nearest weather station. This dataset was supplemented with observations from experimental fires (Lavoie and Taylor, 2007) and operational prescribed fires (Kubian, 2013). At this time, their analysis has incorporated 14 observations of fire spread rates ranging from ~1 to near 70 m min^{-1} and Initial Spread Index component values (Van Wagner, 1987) ranging from ~5 to 23. Preliminary results of the analysis suggests that there is a 2.7 times increase in rate of spread in lodgepole pine stands 1–6 years after attack when compared with predictions based on FBP System fuel type C-3.

Conclusions

True insight into understanding and predicting the possible effects of recent MPB-caused tree mortality on surface and crown fire potential in lodgepole pine forests has so far proven to be largely an intractable problem. While significant progress has been made in recent years documenting the effects of MPB-related tree mortality on fuel complex structure as well as seasonal and diurnal fuel moistures, trying to accurately assess potential fire behaviour using either operational or physics-based fire behaviour models has proven problematic. Except for the recent development in British Columbia, Canada, with respect to a statistical model (Perrakis *et al*., 2012), existing models tend to be either inappropriate and/or un-validated for use in MPB-attacked forests. Current operational fire behaviour models used in the US are not capable of addressing the complex spatial arrangements of crown fuels that occur in recently attacked stands. Physics-based models such as WFDS may in time serve to be useful research tools and aid in understanding the dynamic nature of fire behaviour, but until the limitations and sources of error are better understood, interpretations of the resulting simulations must be viewed with scepticism (Alexander and Cruz, 2013a).

Observations from experimental fires and wildfires indicate that a real and considerable increase in crown fire potential exists in recently attacked stands with an increase in rate of spread on the order of 2 –3 times the no-tree mortality predictions. However, the amount of red foliage within the canopy has important implications on the duration of the increased crown fire hazard. Site-specific factors such as the total and yearly amount of tree mortality, the length of the outbreak, and the pre-existing stand conditions could all be important factors that could affect the severity and duration of the crown fire hazard. Additional factors such as the juxtaposition of red and green crowns and the relative importance of needle drop and subsequent decreases in CBD *vs* the increased flammability of red foliage may be important to evaluating crown fire hazard but as yet are not fully understood.

Limitations in the ability to accurately assess crown fire potential in MPB-affected stands are likely to persist until accurate wildfire observations and/or experimental fires can be used to either validate current fire behaviour models or derive the needed empirical proportionality constants in Van Wagner's (1977) crown fire initiation and propagation models applicable to MPB-attacked stands. A program of experimental fires (Alexander and Quintilio, 1990; Stocks *et al*., 2004a) coupled with more systematic monitoring and documentation of wildfires (Alexander and Taylor, 2010) is needed in order to address these current shortcomings and gain insight into the underlying processes controlling fire behaviour in MPB fuel complexes. It is a shocking admission that the only empirical investigation of fire behaviour in live, lodgepole pine stands is limited to a single study, involving surface fires, carried out in British Columbia, Canada, 45 years ago (Lawson, 1972; 1973). Additional information on the physical processes of foliage ignition and the relative effect of moisture content under varying heat fluxes will also aid in the development and modification of physics-based

Downloaded from http://forestry.oxfordjournals.org/ by guest on February 26, 2014

models that would greatly enhance our understanding of fire behaviour in these forest ecosystems (Mäkelä *et al*., 2000).

As the number and size of MPB outbreaks in western North America declines, opportunities to conduct experimental fires and observe fire behaviour in recently attacked stands will decrease. Simulating MPB-attack, similar to Schroeder and Mooney (2009; 2012), by girdling trees provides a potential way to extend the window of opportunity for experimental fires and to control for confounding factors. Investments in gathering and compiling fire behaviour data by fire management and fire research organizations will help provide a means to objectively assess fire behaviour potential in this unique fuel complex, which will increase the margin of safety for future wildland firefighters and aid in operational planning for fire managers. Meanwhile, wildland firefighters should continue to be vigilant in recently attacked MPB-affected lodgepole pine forests and follow the guidelines outlined in the fire environment factors listed in the 'Look Up, Down and Around' table for insect-killed forests found in the Incident Response Pocket Guide (National Wildfire Coordinating Group, 2010).

Acknowledgements

Thanks to W.E. Lindquist for assistance with graphics. The comments of O.B. Armitage, B.J. Bentz, M.G. Cruz, J.G. Klutsch, M.R. Kuhns, D. Quintilio, R.D. Wilmore and anonymous reviewers on earlier drafts of this article were appreciated. We would like to thank D.T. Hicks with the British Columbia Forests, Lands and Natural Resources Operations, Prince George, BC, for hosting our visit in May 2012 to learn more about the research and operational monitoring of fire behaviour in MPB-attacked lodgepole pine forests in the north-central part of the province.

Funding

This work was supported by the Joint Fire Science Program Projects 11-1-4-16 and 09-S-03-1.

Conflict of interest statement

None declared.

References

Agee, J.K. 1996 The influence of forest structure on fire behavior. In *Proceedings of the 17th Annual Forest Vegetation Management Conference*, Sherlock, J. (ed), pp. 52–68.

Alexander, M.E. 1979 Fuels description in lodgepole pine stands of the Colorado Front Range. Colo. State Univ., M.Sc. thesis. 150 p.

Alexander, M.E. 1982 Calculating and interpreting forest fire intensities. *Can. J. Bot*. **60**, 349–357.

Alexander, M.E. and Cruz, M.G. 2006 Evaluating a model for predicting active crown fire rate of spread using wildfire observations. *Can. J. For. Res.* **36**, 3015–3028.

Alexander, M.E. and Cruz, M.G. 2011 Crown fire dynamics in conifer forests. In *Synthesis of knowledge of extreme fire behavior: volume I for fire managers*. Werth, P.A., Potter, B.E., Clements, C.B., Finney, M.A., Goodrick, S.L., Alexander, M.E., Cruz, M.G., Forthofer, J.A. and McAllister, S.S. (eds), USDA For. Serv. Gen. Tech. Rep. PNW-GTR-854, , pp. 107–144.

Alexander, M.E. and Cruz, M.G. 2012 Interdependencies between flame length and fireline intensity in predicting crown fire initiation and crown scorch height. *Int. J. Wildland Fire* **21**, 95–113.

Alexander, M.E. and Cruz, M.G. 2013a Are the applications of wildland fire behaviour models getting ahead of their evaluation again? *Environ. Modell. Software*. **41**, 65–71.

Alexander, M.E. and Cruz, M.G. 2013b Assessing the effect of foliar moisture on the spread rate of crown fires. *Int. J. Wildland Fire* **22**, 415–427, 869–870.

Alexander, M.E. and Quintilio, D. 1990 Perspectives on experimental fires in Canadian forestry research. *Math. Comput. Model*. **13**(12), 17–26.

Alexander, M.E. and Taylor, S.W. 2010 Wildland fire behavior case studies and the 1938 Honey Fire controversy. *Fire Manage. Today*. **70**(1), 15–25.

Amin, H., Atkins, P.T., Russo, R.S., Brown, A.W., Sive, B., Hallar, A.G. and Huff-Hartz, K.E. 2012 Effect of bark beetle infestation on secondary organic aerosol precursor emissions. *Environ. Sci. Technol*. **46**, 5696–5703.

Anderson, H.E. 1969 *Heat Transfer and Fire Spread*. USDA For. Serv. Res. Pap. INT-69, 20 pp.

Anderson, H.E. 1982 *Aids to Determining Fuel Models for Estimating Fire Behavior*. USDA For. Serv. Gen. Tech. Rep. INT-122, 22 pp.

Andrews, P.L., Bevins, C.D. and Seli, R.C. 2008 *BehavePlus Fire Modeling System, Version 4.0: user's Guide*. USDA For. Serv. Gen. Tech. Rep. RMRS-106WWW Revised, 123 pp.

Armitage, O.B. 2004 *Fire Behaviour in Mountain Pine Beetle-killed Stands: observations from the Summer of 2004*. British Columbia Ministry of Forests, Protection Branch, Int. Rep., .

Bachop, S. 1998 Provincial safety review team: successes and improvements. In *Proceedings Canada/US Wildland Fire Safety Summit*. Greenlee, J. (ed). *Int. Assn. Wildland Fire,* pp. 59–64.

Bentz, B.J., Régnière, J., Fettig, C.J., Hansen, E.M., Hayes, J.L., Hicke, J.A., Kelsey, R.G., Negrón, J.F. and Seybold, S.J. 2010 Climate change and bark beetles of the western United States and Canada: direct and indirect effects. *Bioscience* **60**, 602–613.

Bishop, J. 2007 Technical background of the fireline assessment method (FLAME). In *The Fire Environment – Innovations, Management, and Policy Conference Proceedings*. Butler, B.W. and Cook, W. (comps.). USDA For. Serv. Proc. RMRS-P-46CD, pp. 27–74.

Black, S.H., Kulakowski, D., Noon, B.R. and DellaSala, D.A. 2013 Do bark beetle outbreaks increase wildfire risks in the central U.S. Rocky Mountains? Implications from recent research. *Nat. Area. J.* **33**, 59–65.

British Columbia Ministry of Forests. 1995 *Bark Beetle Management Guidebook*. http://www.for.gov.bc.ca/tasb/legsregs/fpc/fpcguide/beetle/betletoc.htm (accessed on 8 February, 2014).

Brown, J.K. 1981 Bulk densities of non-uniform surface fuels and their application to fire modeling. *For. Sci*. **27**, 667–683.

Brown, J.K. and Bevins, C.D. 1986 *Surface Fuel Loadings and Predicted Fire Behavior for Vegetation Types in the Northern Rocky Mountains*. USDA For. Serv. Res. Note INT-358, , 9 pp.

Bruner, A.D. and Klebenow, D.A. 1979 *Predicting Success of Prescribed Fires in Pinyon–Juniper Woodland in Nevada*. USDA For. Serv. Res. Pap. INT-219, 12 pp.

Byram, G.M. 1959 Combustion of forest fuels. In *Forest Fire: Control and Use*. Davis, K.P. (ed). McGraw-Hill, pp. 61–89.

Church, S., Romero, F., Erskine, I., Evans, L., Camper, D. and Petrilli, A. 2011 *Salt Fire Facilitated Learning Analysis*. http://wildfirelessons.net/documents/Salt_Fire_FLA.pdf (accessed on 8 February, 2014).

Cole, W.E. and Amman, G.D. 1969 *Mountain Pine Beetle Infestations in Relation to Lodgepole Pine Diameters*. USDA For. Serv. Res. Note INT-95, 8 pp.

Downloaded from http://forestry.oxfordjournals.org/ by guest on February 26, 2014

Cruz, M.G. and Alexander, M.E. 2010 Assessing crown fire potential in coniferous forests of western North America: a critique of current approaches and recent simulation studies. *Int. J. Wildland Fire* **19**, 377–398.

Cruz, M.G. and Fernandes, P.M. 2008 Development of fuel models for fire behaviour in maritime pine (*Pinus pinaster* Ait.) stands. *Int. J. Wildland Fire* **17**, 194–204.

Cruz, M.G., Alexander, M.E. and Wakimoto, R.H. 2005 Development and testing of models for predicting crown fire rate of spread in conifer forest stands. *Can. J. For. Res.* **35**, 1629–1639.

Cullingham, C.I., Cooke, J.E., Dang, S., Davis, C.S., Cooke, B.J. and Coltman, D.W. 2011 Mountain pine beetle host-range expansion threatens the boreal forest. *Mol. Ecol.* **20**, 2157–2171.

Deeming, J.E., Burgan, R.E. and Cohen, J.D. 1977 *The National Fire-Danger Rating System – 1978*. USDA For. Serv. Gen. Tech. Rep. INT-39, 63 pp.

Dimitrakopoulos, A.P. and Papaioannou, K.K 2001 Flammability assessment of Mediterranean forest fuels. *Fire Technol.* **37**, 143–152.

Farrar, J. 1995 *Trees in Canada*. Fitzhenny & Whiteside Limited and Canadian Forest Service, 502 pp.

Forestry Canada Fire Danger Group. 1992 *Development and structure of the Canadian Forest Fire Behavior Prediction System*. For. Can. Inf. Rep. ST-X-3, . 63 pp.

Hester, D.A. 1952 The pinyon–juniper fuel type can really burn. *Fire Control Notes* **13**, 26–29.

Hicke, J.A., Johnson, M.C., Hayes, J.L. and Preisler, H.K. 2012 Effects of bark beetle-caused tree mortality on wildfire. *For. Ecol. Manage.* **271**, 81–90.

Hoffman, C., Morgan, P., Mell, W., Parsons, R., Strand, E.K. and Cook, S. 2012 Numerical simulation of crown fire hazard immediately after bark beetle-caused mortality in lodgepole pine forests. *For. Sci.* **58**, 178–188.

Hoffman, C.M., Morgan, P., Mell, W., Parsons, R., Strand, E. and Cook, S. 2013 Surface fire intensity influences simulated crown fire behavior in lodgepole pine forests with recent mountain pine beetle-caused tree mortality. *For. Sci.* **59**, 390–399.

Jenkins, M.J., Hebertson, E., Page, W. and Jorgensen, C.A. 2008 Bark beetles, fuels, fires and implications for forest management in the Intermountain West. *For. Ecol. Manage.* **254**, 16–34.

Jenkins, M.J., Page, W.G., Hebertson, E.G. and Alexander, M.E. 2012 Fuels and fire behavior dynamics in bark beetle-attacked forests in Western North America and implications for fire management. *For. Ecol. Manage.* **275**, 23–34.

Jenkins, M.J., Runyon, J.B., Fettig, C.J., Page, W.G. and Bentz, B.J. 2014 Interactions among the mountain pine beetle, fires, and fuels. *For. Sci.* **60**, (in press).

Jolly, W.M., Parsons, R., Varner, J.M., Butler, B.W., Ryan, K.C. and Gucker, C.L. 2012a Do mountain pine beetle outbreaks change the probability of active crown fire in lodgepole pine forests? Comment. *Ecology.* **93**, 941–946.

Jolly, W.M., Parsons, R.A., Hadlow, A.M., Cohn, G., McAllister, S., Popp, J.B., Hubbard, R.M. and Negrón, J.F. 2012b Relationships between moisture, chemistry, and ignition of *Pinus contorta* needles during the early stages of mountain pine beetle attack. *For. Ecol. Manage.* **269**, 52–59.

Keyes, C.R. 2006 Role of foliar moisture content in the silvicultural management of forest fuels. *West. J. Appl. For.* **21**, 228–231.

Klutsch, J.G., Negrón, J.F., Costello, S.L., Rhoades, C.C., West, D.R., Popp, J. and Caissie, R. 2009 Stand characteristics and downed woody debris accumulations associated with a mountain pine beetle (*Dendroctonus ponderosae* Hopkins) outbreak in Colorado. *For. Ecol. Manage.* **258**, 641–649.

Klutsch, J.G., Battaglia, M.A., West, D.R., Costello, S.L. and Negrón, J.F. 2011 Evaluating potential fire behavior in lodgepole pine-dominated forests after a mountain pine beetle epidemic in north-central Colorado. *West. J. Appl. For.* **26**, 101–109.

Kubian, R. 2013 *The impact of mountain pine beetle on fire behaviour – a case study of the Mitchell Ridge prescribed burn*. Kootenay National Park. http://foothillsri.ca/sites/default/files/null/MPBEP_2010_09_Prsnttn_ImpactofMPBonFireBehaviourMitchellRidgeCaseStudy.pdf (accessed on 8 February, 2014).

Lavoie, N. and Taylor, S. 2007 *Carrott Lake Project – May 2007 Update*. B.C. Min. For. Prot. Progr. Int. Rep. 7 pp.

Lawson, B.D. 1972 Fire spread in lodgepole pine stands. Univ. Mont., M.Sc. thesis, 119 p.

Lawson, B.D. 1973 *Fire Behavior in Lodgepole Pine Stands Related to the Canadian Fire Weather Index*. Can. For. Serv. Inf. Rep. BC-X-176. 26 pp.

Lawson, B.D. and Armitage, O.B. 2008 *Weather guide for the Canadian Forest Fire Danger Rating System*. Can. For. Serv. North. For. Cent. 73 pp.

Linn, R.R., Reisner, J., Colman, J.J. and Winterkamp, J. 2002 Studying wildfire behavior using FIRETEC. *Int. J. Wildland Fire.* **11**, 233–246.

Linn, R.R., Sieg, C.H., Hoffman, C.M., Winterkamp, J. and McMillin, J.D. 2013 Modeling wind fields and fire propagation following bark beetle outbreaks in spatially-heterogeneous pinyon–juniper woodland fuel complexes. *Agric. For. Meteorol.* **173**, 139–153.

Mäkelä, A., Landsberg, J., Ek, A.R., Burk, T.E., Ter-Mikaelian, M., Agren, G.I., Oliver, C.D. and Puttonen, P. 2000 Process-based models for forest ecosystem management: current state of the art and challenges for practical implementation. *Tree Physiol.* **20**, 289–298.

Meddens, A.J.H., Hicke, J.A. and Ferguson, C.A. 2012 Spatiotemporal patterns of observed bark beetle-caused tree mortality in British Columbia and the western United States. *Ecol. Appl.* **22**, 1876–1891.

Mell, W., Jenkins, M.A., Gould, J. and Cheney, P. 2007 A physics based approach to modeling grassland fires. *Int. J. Wildland Fire.* **16**, 1–22.

Moran, C.J. and Cochrane, M.A. 2012 Do mountain pine beetle outbreaks change the probability of active crown fire in lodgepole pine forests? Comment. *Ecology.* **93**, 939–941.

McRae, D.J., Alexander, M.E. and Stocks, B.J. 1979 *Measurement and Description of Fuels and Fire Behavior on Prescribed Burns: A Handbook*. Can. For. Serv. Inf. Rep. O-X-287. 44 pp.

National Interagency Fire Center. 2011 *Central Idaho Fuels and Fire Behavior Advisory: Changes in Lodgepole Pine Flammability Due to Mountain Pine Beetle Infestation*. http://www.wildlandfire.com/docs/2011/safe/CID_Fuels_Fire_Behavior_Advisory_09062011.pdf (accessed on 8 February, 2014).

National Wildfire Coordinating Group. 2010 *Incident Response Pocket Guide*. Nat. Inter. Fire Center Publ. NFES 1077, .

Page, W.G. and Jenkins, M.J. 2007a Mountain pine beetle-induced changes to selected lodgepole pine fuel complexes within the intermountain region. *For. Sci.* **53**, 507–518.

Page, W.G. and Jenkins, M.J. 2007b Predicted fire behavior in selected mountain pine beetle-infested lodgepole pine. *For. Sci.* **53**, 662–674.

Page, W.G., Jenkins, M.J. and Runyon, J.B. 2012 Mountain pine beetle attack alters the chemistry and flammability of lodgepole pine foliage. *Can. J. For. Res.* **42**, 1631–1647.

Page, W.G., Alexander, M.E. and Jenkins, M.J. 2013a Wildfire's resistance to control in mountain pine beetle-attacked lodgepole pine forests. *For. Chron.* **89**, 783–794.

Page, W.G., Jenkins, M.J. and Alexander, M.E. 2013b Foliar moisture content variations in lodgepole pine over the diurnal cycle during the red stage of mountain pine beetle attack. *Environ. Modell. Software.* **49**, 98–102.

Perrakis, D., Hicks, D., Lanoville, R., Taylor, S., Lavoie, N., Pritchard, M. and Kubian, R. 2012 *Recent Observations of Fire Behaviour in Mountain Pine Beetle-Affected Forest Stands*. http://www.ualberta.ca/~wildfire/Wildland_Fire_Canada/2012%20PDF/Dan%20Perrakis.pdf (accessed on 8 February, 2014).

Downloaded from http://forestry.oxfordjournals.org/ by guest on February 26, 2014

Pompe, V. and Vines, R.G. 1966 The influence of moisture on the combustion of leaves. *Aust. For.* **30**, 231–241.

Renkin, R.A. and Despain, D.G. 1992 Fuel moisture, forest type and lightning-caused fire in Yellowstone National Park. *Can. J. For. Res.* **22**, 37–45.

Rocca, M.E. 2010 Final Report: Forecasting Impacts of Mountain Pine Beetle on Lodgepole Pine Forests. http://www.cfc.umt.edu/CESU/Reports/NPS/CSU/2008/08_09Rocca_ROMO_pine%20beetle_lodgepole%20final%20rpt.pdf (accessed on 8 February, 2014).

Rossi, J.P., Samalens, J.C., Guyon, D., van Halder, I., Jactel, H., Menassieu, P. and Piou, D. 2009 Multiscale spatial variation of the bark beetle *Ips sexdentatus* damage in a pine plantation forest (Landes de Gascogne, Southwestern France). *For. Ecol. Manage.* **257**, 1551–1557.

Rothermel, R.C. 1972 *A mathematical model for predicting fire spread in wildland fuels*. USDA For. Serv. Res. Pap. INT-115, 40 pp.

Rothermel, R.C. 1991 *Predicting behavior and size of crown fire in the Northern Rocky Mountains*. USDA For. Serv. Res. Pap. INT-438, 46 pp.

Safranyik, L., Carroll, A.L., Régnière, J., Langor, D.W., Riel, W.G., Shore, T.L., Peter, B., Cooke, B.J., Nealis, V.G. and Taylor, S.W. 2010 Potential for range expansion of mountain pine beetle into the boreal forest of North America. *Can. Entomol.* **142**, 415–442.

Salazar, L.A. and Bevins, C.D. 1984 *Fuel Models to Predict Fire Behavior in Untreated Conifer Slash*. USDA For. Serv. Res. Note PSW-370, 6 pp.

Schmid, J.M. and Amman, G.D. 1992 Dendroctonus beetles and old-growth forests in the Rockies. In *Proceedings of a Workshop, Old-growth Forests in the Southwest and Rocky Mountain Regions*. Kaufmann, M.R., Moir, W.H. and Bassett, R.L. (eds). *USDA For. Serv. Gen. Tech. Rep. RM-GTR-213,* pp. 51–59.

Schoennagel, T., Veblen, T.T., Negrón, J.F. and Smith, J.M. 2012 Effects of mountain pine beetle on fuels and expected fire behavior in lodgepole pine forests, Colorado, USA. *PLoS ONE* **7**, e30002.

Schroeder, D. and Mooney, C. 2009 Fire behaviour in simulated mountain pine beetle attacked stands, interim report, 2008 Archer Lake burn trials. FPInnovations Wildfire Operations Research Group. http://wildfire.fpinnovations.ca/64/Archer2008Report.pdf (accessed on 8 February, 2014).

Schroeder, D. and Mooney, C. 2012 Fire behaviour in simulated mountain pine beetle-killed stands, final report. FPInnovations Wildfire Operations Research Group. http://wildfire.fpinnovations.ca/64/ArcherMPB_Final.pdf (accessed on 8 February, 2014).

Scott, J.H. and Burgan, R.E. 2005 *Standard Fire Behavior Fuel Models: A Comprehensive Set for Use with Rothermel's Surface Fire Spread Model*. USDA For. Serv. Gen. Tech. Rep. RMRS-GTR-153, 72 pp.

Scott, J.H. and Reinhardt, E.D. 2001 *Assessing Crown Fire Potential by Linking Models of Surface and Crown Fire Behavior*. USDA For. Serv. Res. Pap. RMRS-RP-29, 59 pp.

Simard, M., Romme, W.H., Griffin, J.M. and Turner, M.G. 2011 Do mountain pine beetle outbreaks change the probability of active crown fire in lodgepole pine forests? *Ecol. Monogr.* **81**, 3–24.

Simard, M., Romme, W.H., Griffin, J.M. and Turner, M.G. 2012 Do mountain pine beetle outbreaks change the probability of active crown fire in lodgepole pine forests? Reply. Ecology **93**, 946–950.

Stiger, E.M. and Infanger, C.R. 2011 Fire behavior observations in beetle killed trees in Lewis & Clark, Jefferson, Broadwater, and the southwest portion of Cascade county. In *Proceedings of 11th International Wildland Fire Safety Summit*. Fox, R.L. (ed). *Int. Assn. Wildland Fire. CD-ROM*. 3 pp.

Stocks, B.J. 1987 Fire potential in the spruce budworm-damaged forests of Ontario. *For. Chron.* **63**, 8–14.

Stocks, B.J., Alexander, M.E. and Lanoville, R.A. 2004a Overview of the International Crown Fire Modelling Experiment (ICFME). *Can. J. For. Res.* **34**, 1543–1547.

Stocks, B.J., Alexander, M.E., Wotton, B.M., Stefner, C.N., Flannigan, M.D., Taylor, S.W., Lavoie, N., Mason, J.A., Hartley, G.R., Maffey, M.E., Dalrymple, G.N., Blake, T.W., Cruz, M.G. and Lanoville, R.A. 2004b Crown fire behaviour in a northern jack pine-black spruce forest. *Can. J. For. Res.* **34**, 1548–1560.

Sullivan, A.L. 2009 Wildland surface fire spread modelling, 1990–2007. 1: physical and quasi-physical models. *Int. J. Wildland Fire* **18**, 349–368.

Taylor, S.W., Pike, R.G. and Alexander, M.E. 1997 *A Field Guide to the Canadian Forest Fire Behavior Prediction (FBP) System*. Can. For. Serv. North. For. Cen. Spec. Rep. 11., 60 pp.

Thomas, P.H. 1967 Some aspects of the growth and spread of fire in the open. *Forestry* **40**, 139–164.

Thomas, D.A. 1991 The Old Faithful fire run of September 7, 1988. In *Proceedings of 11th Conference on Fire and Forest Meteorology*. Andrews, P.L. and Potts, D.F. (eds). *Soc. Amer. For. SAF Publ. 91–04,* pp. 272–280.

Van Wagner, C.E. 1971 *Two Solitudes in Forest Fire Research*. Can. For. Serv. Inf. Rep. PS-X-29, 7 pp.

Van Wagner, C.E. 1977 Conditions for the start and spread of crown fire. *Can. J. For. Res.* **7**, 23–34.

Van Wagner, C.E. 1987 *Development and structure of the Canadian Forest Fire Weather Index System*. Can. For. Serv. For. Tech. Rep. 35, 37 pp.

Van Wagner, C.E. 1989 Prediction of crown fire behavior in conifer stands. In *Proceedings of the 10th Conference on Fire and Forest Meteorology*. MacIver, D.C., Auld, H. and Whitewood, R. (eds). For. Can. and Environ. Can., pp. 207–212.

Downloaded from http://forestry.oxfordjournals.org/ by guest on February 26, 2014