Wildfire's resistance to control in mountain pine beetle-attacked lodgepole pine forests

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

ABSTRACT

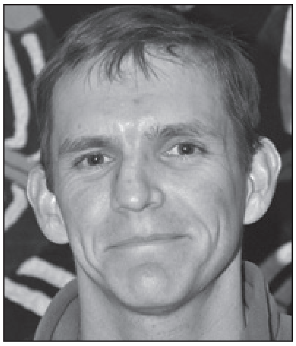
Concerns about the impacts of mountain pine beetle (*Dendroctonus ponderosae* Hopkins)-caused tree mortality on wildfire potential in lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) forests have to date largely focused on the potential for extreme fire behaviour, including the development and spread of crown fires. Given that the wildland fire environment in which fire managers and firefighters work is composed of many interacting physical and human factors, viewing crown fire behaviour 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 paper we describe a holistic concept of analyzing the impacts of mountain pine beetle-caused tree mortality on wildfire potential in lodgepole pine forests on the basis of fire behaviour characteristics, fire suppression operations, and firefighter safety considerations within the framework of three recognizable stages of the approximate time since the initiation of an outbreak (i.e., "red" ~1 to 5 years, "gray" ~5 to 15 years, and post-epidemic ~15+ years).

Key words: fire behaviour, fire hazard, fire suppression, firefighter safety, forest fuels, tree mortality.

RÉSUMÉ

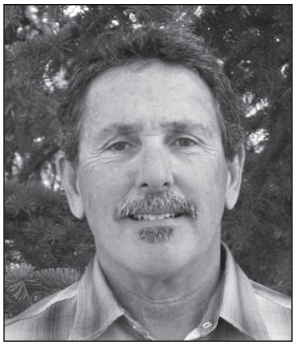
Les inquiétudes rattachées aux effets de la mortalité des arbres causée par le dendroctone du pin (*Dendroctonus ponderosae* Hopkins) sur les feux de forêts au sein des peuplements de pin lodgepole (*Pinus contorta* Dougl. var. *latifolia* Engelm.) ont principalement porté à ce jour sur la possibilité d'observer un comportement extrême des feux, incluant le développement et la propagation des feux de cimes. Étant donné que l'environnement des feux de forêts dans lequel travaillent les gestionnaires et les pompiers forestiers est composé de plusieurs facteurs physiques et humains en interaction, considérer le comportement des feux de cimes comme étant la seule ou encore la plus importante conséquence de la mortalité des arbres associée à l'épidémie de dendroctone du pin peut être discutable. L'évaluation adéquate du potentiel d'inflammabilité implique une approche plus globale, ce qui nécessite d'élargir le concept de résistance des feux de forêt au contrôle pour y inclure une analyse de tous les facteurs pertinents et de leurs interactions. Dans cet article, nous décrivons un concept holistique d'analyse des impacts de la mortalité des arbres causée par le dendroctone du pin sur l'inflammabilité des peuplements de pin lodgepole en se basant sur les caractéristiques du comportement du feu, les opérations de suppression du feu et les aspects de sécurité des pompiers dans le cadre de trois niveaux identifiables de temps approximativement écoulé depuis le début d'une épidémie (c'est-à-dire, « rouge » ~1 à 5 ans, « gris » ~5 à 15 ans et post-épidémie ~15+ ans).

Mots clés : comportement du feu, risque de feu, suppression du feu, sécurité des pompiers, combustibles forestiers, mortalité des arbres



Wesley G. Page

Martin E. Alexander



Michael J. Jenkins

[1]Department of Wildland Resources, Utah State University, 5230 Old Main Hill, Logan, Utah 84322-5230.
[2]Department of Renewable Resources and Alberta School of Forest Science and Management, University of Alberta, Edmonton, Alberta T6G 2H1.
[*]Corresponding author. E-mail: mea2@telus.net

Introduction

The most recent outbreaks of mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins) in lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) forests of western North America began slightly more than a decade ago and have affected more than 7 million hectares (Meddens *et al.* 2012). Some of the highest levels of mortality have occurred in the lodgepole pine forests of central and southern British Columbia and the Rocky Mountains of the western U.S. with mortality frequently reported to exceed 70% of the total stand basal area (Brown *et al.* 2010, Collins *et al.* 2012). Current projected changes in climate have also led to fears that the outbreak may expand beyond the species' historic range (Safranyik *et al.* 2010, Hyenegaard 2012). Naturally, the tree mortality associated with such outbreaks, and the vast areas affected or at risk, has raised concerns about the potential for increased levels in fire behaviour characteristics in affected stands (Jenkins *et al.* 2008), which has prompted land managers to assess the need for fuel treatments to mitigate potential dangers (USDA Forest Service 2011).

Simard *et al.* (2011), and in turn Black *et al.* (2013), for example, have suggested on the basis of fire behaviour simulations, that an increase in the probability of active crown fire is unlikely in affected stands and that treatments to mitigate the impacts of mortality are therefore unwarranted. This conclusion may have been based on the premise that crown fires are beyond the limits of control by conventional means of fire suppression (Alexander and Cruz 2013). Indeed, the increase in the likelihood of active crowning compared to the endemic or pre-attack condition (Fig. 1a) may be limited to a two- or three-year period immediately following MPB attack (Jenkins *et al.* 2008, Hicke *et al.* 2012). However, this does not negate the possibility of other issues to be considered in terms of wildfire potential, including wildfire occurrence, other aspects of fire behaviour such as spotting, and the ability to conduct safe and effective fire suppression operations. For example, a broader view than just the consideration of increased active crowning is the recognition that people (i.e., firefighters and also members of the general public) are part of the wildland fire environment in these affected forests (Barrows 1974, Stiger 2012).

The purpose of this paper is to present and discuss a comprehensive approach to assessing the impacts of MPB-related tree mortality on wildfire potential by broadening the scope of the traditional concept of wildfire's "resistance to control" (Alexander 2000). Resistance to control provides an ideal framework to address the impacts associated with MPB-induced tree mortality in that it incorporates many of the aspects that the wildland fire management community is directly concerned with or responsible for through their stewardship of forested lands. Others have clearly discussed the important ecological role that the MPB plays in lodgepole pine forests (e.g., Brown 1975); however, as these forests do not exist in a vacuum, the impacts of MPB mortality can only truly be assessed within the context of the human environment, which includes the priorities and responsibilities of forest management. As many of the specific details associated with MPB-induced tree mortality have yet to be studied, some implications are based on comparable work conducted in different contexts or based on the personal observations of fire managers and firefighters (Stiger and Infanger 2011; Box 1).

Box 1. Firefighters and fire managers have made several observations in mountain pine beetle affected lodgepole pine forests in recent years (as quoted in Stiger and Infanger 2010 based on their own observations and conversations with other fire managers).

Crowning

Bill Cyr, (Lincoln, Montana Fire Chief and Department of Natural Resources and Conservation Fire Forester, Montana, USA).

> "In red/dead lodgepole pine the pitch tubes seem to be acting as ladder fuels providing a means for fire to move up the trunk of the tree and into the crowns."

Bob Drake, (Tri-Lakes Fire Chief, Helena, Montana, USA).

> "It appears that the red/dead provides the ignition source to start a crown fire that is then carried by the volatiles in the green trees."

Greg Archie, (Department of Natural Resources and Conservation, Central Land Office, Fire Program Manager, Helena, Montana, USA).

> "[based on observations of the Davis wildfire, Fig. 1(e), with 50 to 75% red/dead component] …it was astounding how fast the crown fire gained momentum and spread as a crown fire from an initiating small spot fire. This occurred under rather mundane weather conditions with air temperatures in the 70°F's and relative humidity near 20% with relatively light winds."

Spotting

Jay Lindgren, (U.S. Forest Service, Helena National Forest, Lincoln District Fire Management Officer, Lincoln, Montana, USA).

> "[description based on the smoke from crowning lodgepole pine with more than 50% red/dead component]…, the blackest smoke he had ever witnessed. This event produced profuse spotting. Such unusual black smoke may be the result of enormous amounts [of] aerodynamic bark and red needles exhibiting incomplete combustion."

E.M. Stiger, (Retired U.S. Forest Service Zone Fuel Management Specialist, currently Fire Behavior Analyst for Tri-County area, Helena, Montana, USA).

> "The Probability of Ignition (POI) may play a more important role in anticipating unusual fire behavior in red/dead pines than previously thought. During the North Fork (of Stickney Creek) fire in July, the POI was estimated at 74 to 86. This fire exhibited mass spotting that spread rapidly in the surface fuels."

Fig. 1. Photographs of lodgepole pine forests in different mountain pine beetle attack stages, (a) endemic or pre-attack condition, note green and mature overstory and sparse understory (photo by W.G. Page), (b) "red" stage, recently attacked lodgepole pine trees (red) intermixed with new attacks (off-green or yellow) and un-attacked trees (green) (photo by M.J. Jenkins), (c) "gray" stage, most or all susceptible lodgepole pine killed and still standing with needles fallen, intermixed with surviving lodgepole pine or non-host species and advanced regeneration in the understory (photo by W.G. Page), and (d) post-epidemic stage, note heavy accumulations of dead and down woody material in "jackstraw" condition intermixed with overstory of mostly non-host species and understory of advanced regeneration (photo by W.G. Page). Wildfires burning through lodgepole pine forests, (e) active crown fire run during the Davis Fire in Montana, August 2010, burning in "red" stage lodgepole pine (photo courtesy of U.S. Forest Service, from Stiger and Infanger 2010) and, (f) high-intensity fire in "gray" stage lodgepole pine in British Columbia, September 2012, Fire R10171 near Entiako Lake (photo by R. Krause, British Columbia Forests, Lands and Natural Resources Operations).

Broadening the Definition of "Resistance to Control"

Resistance to control has been defined as "the relative difficulty of constructing and holding a control line as affected by resistance to line construction and by fire behaviour" (Merrill and Alexander 1987, National Wildfire Coordinating Group 2012). This may also involve the difficulty of mop-up as dictated by a fire's persistence (British Columbia Ministry of Forests 1983). Firefighter safety has not directly been included in this conventional definition. Nevertheless, it is implicit, as constructing and holding a control line is not possible if firefighter safety measures such as lookouts, anchor points, communications, escape routes, and safety zones are not established due to the overriding priority of human life on all wildland fires (Gleason 1991, Alexander 2013).

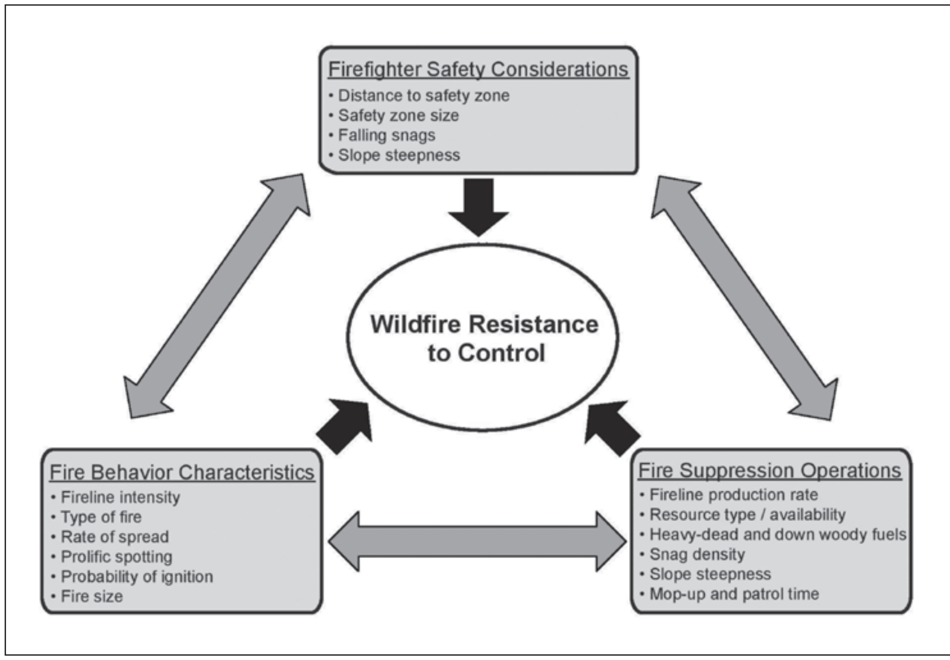


Fig. 2. Conceptual diagram of the three primary factors affecting the resistance to control of wildfires in mountain pine beetle-attacked lodgepole pine forests.

In this paper we include firefighter safety considerations as a distinct component of resistance to control along with fire behaviour characteristics and fire suppression operations, including the rate of fireline construction (Fig. 2). In forests with extensive MPB-caused tree mortality, explicitly including firefighter safety considerations is necessary as it can become decoupled from the resultant fire behaviour situation, as for example, when extremely dangerous stand conditions in the form of high snag densities exist, yet the ensuing fire behaviour may otherwise be mild. Such conditions have been noted in other forests containing high snag densities; for example, in California hardwood forests that have experienced sudden oak death (SOD) due to the pathogen *Phytophthora ramorum* S. Werres & AWAM de Cock (Lee *et al.* 2010). In fact, conditions may exist such that direct suppression by firefighters on the ground may not be possible entirely because of safety concerns as opposed to fire behaviour.

Fire Behaviour Characteristics

The characteristics of the behaviour of free-burning wildland fires generally includes the ignition probability, spread rate, fuel consumed, shape of the fire perimeter, fireline intensity (i.e., rate of energy release at any point about the fire perimeter), flame front dimensions, type of fire (i.e., surface, passive crown, active crown), fire size (area burned and perimeter length), flame residence and burn-out times, and related phenomena such as spotting and fire whirls (Byram 1959, Alexander 2000, Alexander and Cruz 2013). Fires in heavy fuelbeds such as logging slash and blowdown generally exhibit slow spread rates and long flame front residence times whereas fires in light fuel situations like cured grass spread much faster and have very short residence times; fires in conifer forests and shrublands tend to be intermediary (Fig. 3). Fireline intensities can be similar under

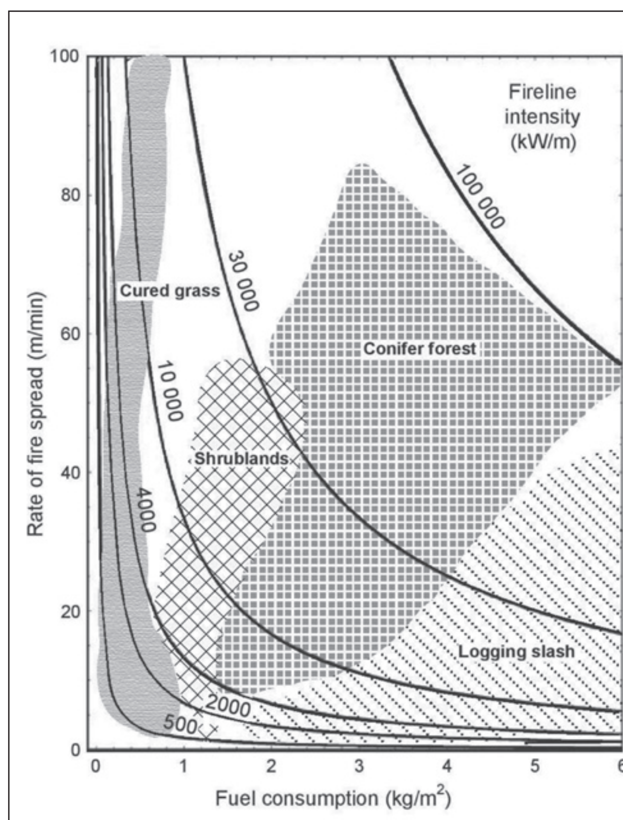


Fig. 3. A fire behaviour characteristics chart (Alexander and Cruz 2012b) showing the general range in rate of spread, fuel consumption and fireline intensity for cured grass, shrubland, conifer forest, and logging slash fuel complexes based on experimental field fires (after Stocks and Kauffman 1997). Numerically, fireline intensity is equal to the product of the net low heat of combustion (18 000 kJ/kg is assumed here), quantity of fuel consumed and the linear rate of spread. Flame size is its main visual manifestation.

different fuel and weather conditions because of varying rates and amounts of fuel consumption (Alexander and Cruz 2012a).

The changes in the characteristics of fire behaviour in MPB-attacked lodgepole pine stands over the course of an outbreak have previously been discussed in detail by Jenkins *et al.* (2008, 2012, 2014) and Hicke *et al.* (2012). Based on their conclusions, in addition to the endemic or pre-attack condition (Fig. 1a), there are at least three distinct periods or stages of stand mortality and structure change following severe MPB attack in lodgepole pine forests that can be described in terms of fire behaviour potential in relation to resistance to control: “red”, “gray”, and post-epidemic (Fig. 1b–d).

During the “red” stage, i.e., about one to five years after outbreak initiation (Fig. 1b), characterized by retention of dead needles, a peak in potential fire behaviour is present (Fig. 4), compared to the pre-attack condition, due largely to the effects of low foliar moisture content and high flammability on crown ignition (Fig. 1e) (Jolly *et al.* 2012; Page *et al.* 2012, 2013). The likelihood of such a crown fire event increases with slope steepness (Van Wagner 1977). Hazards associated with short-range spotting, including directly into the red tree crowns themselves, combined with the potential for long-distance spotting due to strong convection column development associated with the crowning (Box 1), can also substantially increase potential fire behaviour (Jenkins *et al.* 2012) (Table 1).

During the “gray” stage, i.e., approximately five to 15 years after outbreak initiation (Fig. 1c)—when the dead trees lose their needles but remain standing as snags, there is generally considered to be a decrease in crowning potential as the possibility of an active crown fire occurring declines due to the loss of canopy foliage at both the individual tree and stand levels (Fig. 4) (Hicke *et al.* 2012). However, this does not preclude other aspects of extreme fire behaviour, such as large increases in fireline intensity (Fig. 1f).

The significant loss of overstory foliage and the resultant exposure of surface fuels to increased solar radiation and wind speed during the “gr ay” stage can also enhance fire spread at the ground surface, resulting in more intense fires than would otherwise occur without tree mortality (Jenkins *et al.* 2008, Gray 2013). Furthermore, the dead, weakened and decayed trees that were attacked by MPB can provide an ample source of large firebrands (e.g., bark flakes, twigs) with long burn-out times that can aid in an increase in spotting density (Hvenegaard 2012) and maximum distance (Albini *et al.* 2012) (Table 1). Some fire managers have also noted a significant increase in grass cover and loading at some sites, raising concerns about fast-burning, high-intensity fires when grasses are cured in the spring and fall (R.D. Wilmore, USDA Forest Service, Eagle, CO, 2013, personal communication).

Following the “gray” stage comes the post-epidemic condition or stage, i.e., ~15+ years after outbreak initiation (Fig. 1d). This stage is characterized by large accumulations of dead and down woody fuel produced by snag fall and the presence of an understory of advanced spruce (*Picea* spp.) or fir (*Abies* spp.) tree reproduction in seral lodgepole pine forests (Pfister and Daubenmire 1975). These conditions can lead to another peak in fire hazard wherein very intense surface fires (Fig. 1f) and passive crown fires (depending on the understory tree structure) are possible (Fig. 4). Note that the timing of the second peak in fire hazard can vary by a host of site-specific factors, including snag fall and decomposition rates and the characteristics of the understory, such as the existence of advanced regeneration (present before attack) or new regeneration (Pelz and Smith 2013). The presence of large amounts of decayed roundwood on the ground (Brown and See 1981) may also provide a receptive fuelbed for hold-over spot fires (Burgan 1966, Stockstad 1979), which can in turn hamper fire suppression operations.

During the early phases of the post-epidemic stage, fires resemble to a certain extent the behaviour of those burning in heavy logging slash or blowdown where large-diameter, downed dead woody fuels produce high fireline intensities but relatively slow to moderate rates of spread (Quintilio 1972, Johnston 2012). The Sleeping Child Fire that occurred in western Montana during August 1961 is an example of such a fire in a post-gray stage stand (29 to 32 years after MPB attack) that proved difficult to control (Lotan 1976, Jenkins *et al.* 2012). Where grass invasion is widespread, a much more volatile situation is possible when the potential exists for both high rates

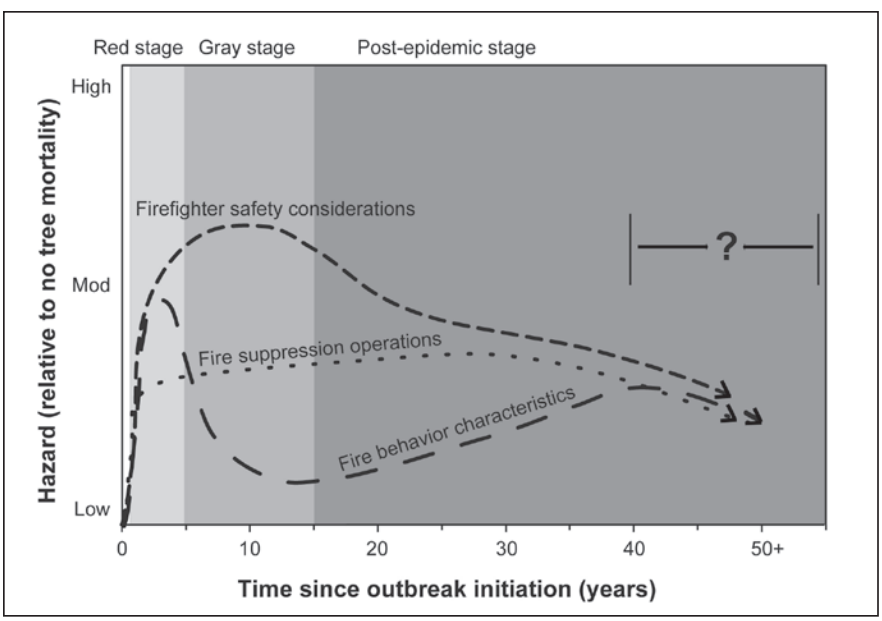


Fig. 4. Summary of the predicted hazard induced by severe tree morality from a mountain pine beetle outbreak in lodgepole pine forests, relative to the case of no tree mortality, for the three main elements of resistance to control, namely, fire behaviour characteristics (e.g., in relation to crowning and fireline intensity), firefighter safety considerations (e.g., in relation to snag conditions), and fire suppression operations (e.g., in relation to spotting and rate of fireline construction). Developed based on summaries by Hicke *et al.* (2012) and Jenkins *et al.* (2008, 2012, 2014). The long-term (50+ years) hazards are currently unknown, as indicated by a question mark.

Table 1. Summary of the potential effects of mountain pine beetle mortality in lodgepole pine forests on fire behaviour, fire suppression operations, and firefighter safety over the course of severe outbreak by bark beetle attack stage (after Jenkins *et al.* 2008, 2012, 2014; Hicke *et al.* 2012)

Impact of concern	Fire behaviour characteristics	Fire suppression operations	Firefighter safety considerations
"Red" stage (~1–5 years after initial attack)			
High density of 'red' trees	• Lower foliar moisture contents of attacked trees may lead to lower fireline intensity threshold for crowning to develop.	• Higher fireline intensities during crowning or when red trees torch decrease direct suppression effectiveness.	•Higher rates of spread decrease escape times to safety zones. •Higher intensity crown fires require greater safety zone sizes.
Long and short distance spotting	• Stronger convection columns during high intensity fires aid in long distance spotting. • Lower foliar moisture contents in red tree crowns increase ignitability, providing a receptive fuel for spotting.	• Fire suppression becomes increasingly difficult as suppression operations become ineffective with long distance spotting. • Short distance spotting into red crowns hampers control operations and requires wider firebreaks.	•Escape routes can become compromised as spot fires cutoff firefighters from safety zones.
Hazard trees (Snags)	• Weakened trees with loose foliage, bark, and branches provide ample firebrand sources for spotting.	• Fireline construction rate is lower due to extra time for snag mitigation.	•Red trees are weak and susceptible to falling, particularly after fire front passage.
"Gray" stage (~5–15 years after initial attack)			
Hazard trees (Snags)	• Standing gray snags have weak and decayed braches and bark providing an ample source for large firebrands with long burn out times.	• Extensive time for snag mitigation is necessary prior to and during fire suppression operations. • Alternative mechanical equipment (i.e., bulldozer) may be necessary for suppression operations.	•Snag mitigation is dangerous and time consuming. •Extremely dangerous post-fire conditions as fire weakened snags fall.
Post-epidemic (~15+ years after initial attack)			
Hazard trees (Snags)	• Remaining snags are old, decayed, and easily weakened by fire passage.	• Total snag density is lower than "gray" stage but remaining snags are rotten and are more difficult and require more time to fall.	•Weak and decayed snags are dangerous to fallers during hazard tree mitigation operations.
Jack straw (dead and down)	• Intense fire behaviour possible with heavy accumulations of dead wood, although may not be classified as crown fires. • Decayed wood provides a receptive fuel bed for spotting.	• Reaching fires in remote locations is difficult and time consuming. • Heavy dead and down make constructing and holding fireline difficult.	•More time required for preparing and using escape routes. •Larger safety zone sizes may be needed due to high intensity fires burning in heavy dead and down woody fuel accumulations.

of spread and high fireline intensities due to the combination of abundant fine fuels and heavy loads of coarse woody fuels. This situation was observed on the 2005 Ophir Mt. Fire in Summit County, Colorado (R.D. Wilmore, USDA Forest Service, Eagle, CO, 2013, personal communication) and has also been observed in post-fire lodgepole pine stands where grasses intermixed with heavy loads of coarse woody fuels such as on the Minto Lake Fire in the Yukon Territory, in 2010, approximately 10 to 15 years post-fire (D.G. Finn, Alberta Environment and Sustainable Resource Development, Rocky Mountain House, AB, 2013, personal communication).

After this second peak in fire behaviour potential, there is presently an uncertainty. There may be a gradual decrease in both surface and crown fire behaviour potential with time, compared to the no-tree mortality case, as woody fuel decomposition and the maturation of the intermediate and understory tree crop returns the affected forest structure closer to pre-outbreak conditions (Fig. 4). The uncertainty arises from our current state of knowledge about late post-epidemic (i.e., 40 to 80 years) fuel characteristics, which is currently limited to model simulations (e.g., Collins *et al.* 2012, Donato *et al.* 2013) and not empirical measurements (Box 2).

Box 2. Research needs and knowledge gaps associated with wildfire resistance to control in mountain beetle-attacked lodgepole pine forests.

Fire behaviour characteristics

- Models of surface fire spread and crown fire potential (initiation and spread) in "red" and "gray" stage stands.
- Snag fall rates in MPB-killed stands.
- Spotting dynamics, including probability of ignition, in MPB-affected fuelbeds.
- Long-term (+40 years) impacts of mortality on stand/fuel conditions and potential fire behaviour, including decomposition rates of downed logs.

Fire suppression operations

- Fireline construction rates by hand and machine in "red", "gray", and post-epidemic stands, including hazard tree mitigation time.
- Effectiveness of indirect suppression strategies.
- Effects of tree mortality on fire cost and duration.

Firefighter safety considerations

- Effectiveness of point or zone protection strategies on decreasing exposure time of firefighters to hazardous conditions.
- Rates of deterioration in standing MPB-killed snags and implications for falling operations.

Fire Suppression Operations

Wildland fire suppression involves all the activities associated with the control and extinguishment of a wildfire following its detection (Brown and Davis 1973, Goodson and Adams 1998). In practical terms, this first means creating a physical barrier (i.e., a fireline) around the fire by one of the following means: (i) removing the fuels or cooling/smothering the flames with water or (ii) covering the fuels with mineral soil, suppressants or chemical fire retardants from either the ground and/or the air. The constructed fireline must then be secured or "held" using effective mop-up. Mop-up requirements can vary substantially by fuel type and site-specific characteristics but usually involve frequent patrolling to ensure that old or new spot fires do not go undetected, removing and/or securing snags or logs that might cross the fireline, and extinguishing any remaining burning material that might be the source for new fire starts (González-Cabán 1984).

During the "red" stage, direct suppression operations may be limited where extensive tree torching and prolific short- and long-range spotting makes holding constructed fireline difficult (Table 1). Indirect methods of fire suppression, such as suppression firing (Cooper 1969), may be needed to effectively deal with the high ignitability of red tree crowns, which can add complexity and additional safety concerns to the fire operations (e.g., unburned fuel between firefighters and the fire). For example, Armitage (2004) recommended the use of mechanical equipment (e.g., bulldozers) to widen firelines in order to effectively deal with the high ignitability of red tree crowns. Normal post-fire patrol and mop-up may also be difficult due to the high densities of MPB-affected trees, which may fall following the initial fire front passage thereby potentially crossing the previously constructed fireline (Table 1).

During the "gray" stage, extensive snag felling by hand or machinery will be necessary both prior to and after passage of the fire front in order to mitigate dangers to firefighters and to maintain the integrity of the fireline. Additionally, snags that catch on fire and remain standing will be exposed to higher wind speeds, increasing the possibility of spotting well after the initial fire front has passed. Depending upon the level of tree mortality, the process of mitigating the problems posed by high snag densities may consume significant periods of time and substantially slow fire suppression operations. Other things being equal, this will lead to an increase in fire size and perimeter length, further increasing the time and effort required for control and extinguishment.

During the post-epidemic phase, heavy accumulations of dead and down woody fuel will substantially slow both the rate of line construction and the process of holding the constructed fireline (Quintilio *et al.* 1990). Analysis of previous (National Wildfire Coordinating Group 1998) and new (Broyles 2011) estimates of direct line construction rates suggest that line construction rate decreases as total fine surface fuel load or fuel resistance increases (Fig. 5). Quantifying the effects of fuel characteristics on line construction rates have met with varying levels of success as the process of constructing and holding fireline can be difficult to measure (Barney 1983, Hirsch and Martell 1996). However, most research has clearly identified a decrease in line construction rate as the number of large dead woody fuel particles increase, either through direct measurement (Murphy and Quintilio 1978, Murphy *et al.* 1989) or by summarizing U.S. Forest Service regional estimates using fuel resistance classes (Haven *et al.* 1982).

In addition to the direct effect of increased fuel loading on line construction rate, increases in fireline intensity and flame length have also been shown to have a negative relationship with fireline production rates (Quintilio *et al.* 1988, Murphy *et al.* 1991, Alexander 2000). Thus, the predicted high-intensity fires in post-epidemic stands could further decrease line construction rate. Furthermore, holding the constructed fireline may prove difficult as the long burn-out times (Beaufait 1961) and high intensities of fires in heavy dead and down woody fuels subject the constructed fireline and the adjacent unburned fuels to prolonged periods of high heat exposure, likely increasing the chances for short-range spotting.

Firefighter Safety Considerations

Firefighter safety has long been recognized as the most important priority on any wildland fire (Jackson 1948). Thus, the concerns associated with firefighter safety have and should take priority over all other actions. In the wildland fire environment, firefighters are confronted with four basic natural safety hazards (Alexander et al. 2012):

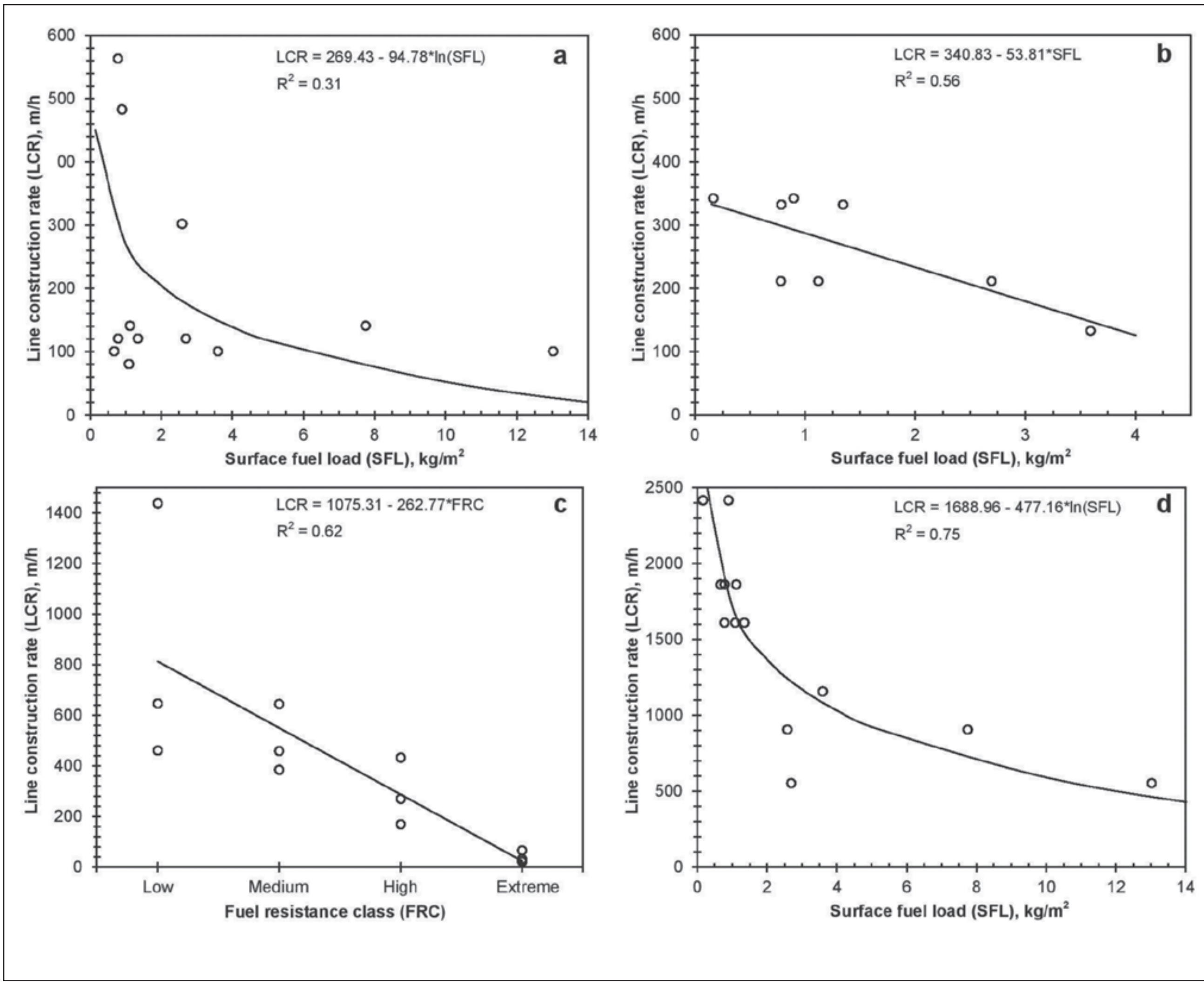


Fig. 5. Plots of observed direct line construction rates and lines of best fit based on linear and non-linear least squares regression for: (a) Type 1 hand crew by fire behaviour fuel models 1 to 13 (Anderson 1982) and total fine surface fuel load (TSFL), using estimates from National Wildfire Coordinating Group (1998), (b) Type 1 hand crew by fire behaviour fuel models 1, 2, 4 to 6, and 8 to 10 and TSFL, based on estimates from Broyles (2011), (c) 20-person hand crew using estimates from Haven *et al.* (1982) for U.S. Forest Service Regions 1, 2, and 4 by fuel resistance class, and (d) Type 1 dozer working uphill (0%–25% slope class) by fire behaviour fuel models 1–13 and TSFL, using the midpoint of estimates from National Wildfire Coordinating Group (1998). The appropriate regression model is displayed in each cell along with the unadjusted r^2 (linear model) and pseudo- r^2 (non-linear model).

- Burn-overs or entrapments by fast-spreading fires
- Snags and fire-weakened timber
- Rolling rocks and logs on steep slopes
- Lightning

To our knowledge there has yet to be a firefighter or civilian fatality associated with a wildfire burning in MPB-attacked lodgepole pine forests, but there have been some close calls. For example, a bulldozer operator and transport driver were burned-over during the Salt Fire in central Idaho during August 2011 (Church et al. 2011). Fortunately, neither was injured.

It is worth noting that firefighter injuries and deaths can also occur directly as part of the fire suppression operations itself (Britton et al. 2013a, 2013b; Cook 2013), irrespective of whether MPB-induced tree mortality is involved. This can result from aircraft (i.e., mechanical failure, rotor downwash and wing-tip vortices), ground-based vehicles (e.g., bulldozer, fire engine, and tractor/plow unit), and hand tools or chainsaws that are involved in containing and/or extinguishing the fire (Teie 2005).

During the “red” stage conditions of MPB attack, firefighter safety concerns generally coincide with the increased potential for high-intensity crown fire behaviour and spotting potential. When fires spreading in surface fuels of conifer forests transition to crowning, at the very minimum they double their spread rate and intensity (Alexander and Cruz 2013). This rapid and dramatic change in the state of fire behaviour will reduce the amount of time available for firefighters to reach safety zones (Alexander *et al.* 2013, Fryer *et al.* 2013). Furthermore, it can increase the size of safety zones needed to adequately protect firefighters (Butler and Cohen 1998, Butler and Putnam 2001). Prolific short- and long-range spotting caused by low ignition thresholds in affected crowns and ample firebrand material on decaying trees can also cut off firefighters from using their escape routes to reach their safety zones. These hazards combine to increase the potential safety issues that wildland firefighters are exposed to and require additional mitigation measures (Fig. 4).

During the "gray" stage, as successfully attacked trees become weakened by decay, the safety hazards associated with wildland firefighting reach peak levels as snag densities can exceed 750 stems/ha (Page and Jenkins 2007). Snags are among the most dangerous threats that firefighters face due to their weakened state and subsequent unpredictability during both normal firefighting and tree felling operations (i.e., the cutting of trees and/or snags down) (Mangan 2007). Recent fatalities associated with falling snags (hitting firefighters), such as on the Steep Corner Fire in central Idaho in 2012 (Foster *et al.* 2013), and with tree/snag felling operations such as on the Eagle Fire in northern California in 2008 (Terrell *et al.* 2013), clearly demonstrate the potential dangers of working in an environment with high snag densities and/or where extensive falling operations are needed.

Beyond the initial hazards posed by snags during burning of "gray" stage forests, there are even greater dangers after the fire front passes. The snags that remain standing are further weakened leading to widespread snag fall for several days, making normal post-fire patrol and mop-up operations especially dangerous, as has been noted following the Basin Complex fires in 2008 in SOD-killed forests in central California (Lee *et al.* 2010). Given the level or risk that firefighters are exposed to in "gray" stage stands it is probable that direct action by personnel on the ground may not be possible and only equipment with reinforced steel cages may be safely operated.

As affected stands enter the post-epidemic phase and the snags continue to deteriorate and fall, the density of snags decreases but those that remain are weak and likely rotten. While mitigation measures such as hazard-tree falling may continue to be possible (Manning *et al.* 2000), the decayed trees are difficult and dangerous to fall due to a lack of adequate holding wood and the presence of "widow-makers" (i.e., trees or snags that have detached or broken limbs or tops) (Peters 1991, Myers and Fosbroke 1994, National Institute of Occupational Safety and Health 1995).

The transfer of snags to the surface also creates what is commonly referred to as "jack straw" or "jackpot" conditions (Hirsch *et al.* 1979), where large amounts of dead and downed woody fuel stack on top of each other. These conditions hamper access into and out of the fire area. Travel times by foot to remote fires can become long as firefighters must maneuver over and through the heavy, dead and down woody fuel accumulations, which raises concerns about the ability of firefighters to quickly leave the fire area. Escape times to safety zones may increase because of reduced rates of movement (Alexander *et al.* 2013) or because longer routes are required.

Implications for Fire Research and Fire Management

To predict the full consequences of large-scale MPB mortality on wildfire potential, we suggest that it is necessary to broaden the definition of resistance to control as follows: "the relative difficulty of constructing and holding a control line as determined by the fire suppression operations, fire behaviour characteristics, and firefighter safety considerations" (Fig. 2). That is, the effects of MPB-induced tree mortality on crew safety and the management responses to these changes, must be considered. Fire suppression personnel who have been involved in the control and extinguishment of wildfires in MPB-attacked lodgepole pine forests will have undoubtedly found the idea of a more expanded concept of resistance to control a logical approach (E.M. "Sonny" Stiger, FireSafe Montana, Helena, MT, 2013, personal communication). Researchers who lack this kind of practical field experience may find the suggested approach frustrating at first, as certain models and data are not readily available to enable them to easily conduct simulations and thereby quickly publish their results.

As many of these proposed effects of MPB on resistance to control are based mostly on personal *ad hoc* personal observations, there exists a need for formal documentation of these impacts in the form of wildfire case studies (e.g., Cruz and Plucinski 2007). The analyses undertaken of the effects of SOD-caused changes in fuel structure on potential surface fire behaviour in relation to the capability and productivity of fire suppression resources undertaken by Valachovic *et al.* (2011) represents an excellent example of one type of analysis that needs to be undertaken for MPB-attacked lodgepole pine forests. Hopefully, fire researchers and fire managers alike will be attracted to the field to collect the kind of information that is required in order to ultimately develop the fire modelling systems and related facts needed for properly assessing the impacts of MPB-caused tree mortality on wildfire potential in lodgepole pine forest communities in western North America (Box 2).

Fire management organizations dealing with widespread tree mortality resulting from a MPB outbreak may be faced with a multitude of potential consequences. Given the likely impacts presented here, it is reasonable to predict detectable increases in common attributes of wildland fires, such as time to containment, cost, and the number of injuries, especially on large fires where MPB-related hazards accumulate over time and space. For example, lower fireline production capability may lead to greater resource needs and types (e.g., bulldozers) in order to maintain an equivalent level of fireline production, which may also lead to higher suppression costs or longer duration fires if resource needs cannot be met. Additionally, higher numbers of firefighters and longer duration fires may lead to increases in the likelihood and number of injuries. Britton *et al.* (2013b), for example, found that on large wildfires in the U.S. that the number of person-days of exposure was the best predictor of the occurrence of injuries.

In recognition of the many dangers faced by wildland firefighters in these forests, incident management personnel have already begun to adjust their strategies and tactics to mitigate potential impacts. Point or zone protection strategies as opposed to full perimeter containment are now frequently implemented where values-at-risk are considered low or where the dangers associated with full suppression are considered too great. Recent examples include the High Park and West Fork Fires in Colorado during the 2012 and 2013 fire seasons, respectively (R.D. Wilmore, USDA Forest Service, Eagle, CO, 2013, personal communication). Although the true impacts of these changing management strategies are as yet unknown, within the wildland fire management community it is believed that fire sizes, and accordingly fire suppression costs, will increase but the frequency of firefighter injuries will decrease.

Fire management agencies should also consider supplementing their conventional fire training with operational prescribed fires in MPB fuel complexes (Cheney 1994). This kind of live fire training would provide the opportunity for those firefighters who have limited exposure to such situations to according gain experience.

Conclusions

The impacts of MPB-induced tree mortality in lodgepole pine forests clearly involve much more than just the effects on selected characteristics of fire behaviour. We have argued here that there are three main factors that should be considered in assessing the potential effects of MPB-related tree mortality on a wildfire's resistance to control, namely, fire behaviour characteristics, fire suppression operations, and firefighter safety considerations. An emphasis on extreme fire behaviour potential in most of the research to date has led to an inadequate accounting of the implications for fire suppression and human safety, which has perhaps caused some confusion as to the potential effects of MPB-induced tree mortality on wildfire potential (Gabbert 2010). High-intensity fires, extensive MPB-caused mortality, and their interaction are widely recognized as playing a fundamental role in the ecology of lodgepole pine forests (Brown 1975). However, as long as firefighters are placed in situations where extensive MPB-caused mortality exists, it is vital that proper recognition be given to all the factors that might influence wildfire potential.

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