

RESEARCH ARTICLE

MODELING WILDFIRE SPREAD IN MOUNTAIN PINE BEETLE-AFFECTED FOREST STANDS, BRITISH COLUMBIA, CANADA

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ABSTRACT

The mountain pine beetle (*Dendroctonus ponderosae* Hopkins; MPB) has killed lodgepole pines (*Pinus contorta* Dougl. ex Loud.) across 20 million hectares of central British Columbia, Canada, since the late 1990s, challenging land managers as well as fire management personnel. Although recent studies have used models to simulate how MPB might affect fire spread, very little fire behaviour has been documented in MPB-affected stands. We documented rate of spread (ROS) in experimental fires and wildfires in recent MPB-killed stands in British Columbia using interpretations of oblique photographs, airborne measurements of wildfire spread, and experimental burns. Fire spread observations were used to develop ROS models following the empirical approach of the Canadian Forest Fire Danger Rating System (CFFDRS). Sixteen fire runs were examined that occurred in mature MPB-affected

RESUMEN

El escarabajo de pinos de montaña (*Dendroctonus ponderosae* Hopkins; MPB) ha provocado la muerte del pino contorta (*Pinus contorta* Dougl. ex Loud.) en 20 millones de ha en la Columbia Británica del Canadá desde fines de los 1990s, generando un desafío tanto para los gestores del territorio como para el personal de gestión del fuego. Aunque estudios recientes han usado modelos para simular como el MPB podría afectar la propagación del fuego, el comportamiento del fuego en rodales afectados por MPB ha sido escasamente documentado. Nuestro trabajo documenta la velocidad de propagación (ROS) en fuegos experimentales e incendios en rodales muertos recientemente por acción del BMP en la Columbia Británica, usando interpretaciones de fotografías oblicuas, mediciones de desplazamiento del fuego por acción del viento, y quemas experimentales. También utilizamos observaciones de velocidades de propagación del fuego, para desarrollar modelos de propagación siguiendo la aproximación empírica del Sistema Canadiense de Evaluación de Peligro de Incendios forestales (CFFDRS). Fueron examinadas dieciséis corridas de incendios ocurridas en rodales maduros, afectados

pine stands from 1 to 5 years since peak attack. Observations of ROS were associated with corresponding weather measurements from nearby weather stations and non-linear regression curves were fit to paired ROS and Initial Spread Index (ISI) data according to CFFDRS convention. Although the dataset is less robust than a strictly experimental approach, fires had faster spread and more crown fire than predicted, with a linear average of 2.7 times higher ROS in best fit models than expected for unaffected pine. The most likely crown fire initiation threshold ($P = 0.5$) was ISI 5.5. Fire intensity is likely higher in early post-MPB stands due to increased ROS, lower crowning thresholds, and greater consumption of fine dead branches. Further studies on fire behaviour in MPB-affected stands are needed, but the present findings can help reduce uncertainty in fire and land management decisions in the interim.

después de 1 a 5 años del pico máximo de ataque. Observaciones del ROS fueron asociadas con las correspondientes mediciones meteorológicas de estaciones cercanas, y las curvas de regresión no lineales fueron ajustadas a datos apareados de ROS y del Índice de Propagación Inicial (ISI), de acuerdo a lo estipulado por el CFFDRS. Aunque el conjunto de datos es estrictamente menos robusto que la aproximación experimental, los fuegos tuvieron desplazamientos más rápidos y coronaron más que los pronosticados, con un ROS linear promedio 2.7 veces más alto en los modelos que mejor ajustaban que lo que se esperaba para rodales no afectados. El límite más probable para la iniciación de fuego de copas ($P = 0.5$) fue ISI 5.5. La intensidad es probablemente mayor en rodales en estadios tempranos post MBP debido al incremento del ROS, con límites más bajos para el coronamiento del fuego y un mayor consumo de ramas finas muertas. Más estudios sobre el comportamiento del fuego son necesarios en rodales afectados por MBP, aunque los presentes resultados pueden ayudar, en el interim, a reducir las incertidumbres en las decisiones de manejo de rodales y del fuego.

Keywords: ecological restoration, fire behavior, fire suppression, forest health, pine bark beetle, rate of spread, remote sensing

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INTRODUCTION

The mountain pine beetle (*Dendroctonus ponderosae* Hopkins; MPB hereafter) has affected vast areas of lodgepole pine (*Pinus contorta* Dougl. ex Loud.)-dominated forests in western Canada and the US. The current outbreak (as per Taylor *et al.* 2006) is the largest contributor to a generalized bark beetle eruption of over 50 million hectares since the late 1990s, collectively forming one of the most significant forest disturbance episodes record-

ed in North America (Raffa *et al.* 2008). Surveys suggest that, in British Columbia, the MPB outbreak began in the mid-1990s and affected 18 to 20 million hectares of forest across the interior of the province by 2012. The outbreak peaked between 2004 to 2006, with a declining area of newly affected forest in recent years, primarily due to the depletion of available susceptible lodgepole pine stands (Westfall and Ebata 2011, Walton 2012). The extent of this disturbance dwarfs any previously documented or estimated MPB outbreaks in

western Canada (Taylor *et al.* 2006). The MPB is still active across the continental divide in Alberta, where beetles have also been observed to attack jack pine (*P. banksiana* Lamb.); farther eastward spread of MPB is considered a threat to large portions of the Canadian boreal forest (Cullingham *et al.* 2011). In the United States, 13 western states have been affected by regional MPB outbreaks, collectively affecting several million hectares of forest land (USFS Forest Health Technology Enterprise Team 2011).

As of 2012, the landscape ecology of central British Columbia had been profoundly altered by MPB. Dry forests of the interior plateau, formerly dominated by various age classes of lodgepole pine, became a mosaic of different disturbances. Green-attack, red-attack, and grey-attack stands (colours refer to the crown foliage appearance, and time since MPB attack, of affected trees, as per Wulder *et al.* 2006) became prominent, and eventually dominant as MPB killed over half of the standing volume of pine in the provincial interior during the past decade (Walton 2012). The most severely affected areas in the province are now dominated by dead grey lodgepole pine stands between 5 and 12 years since attack, although smaller patches of recent-attack stage trees are still locally abundant (Westfall and Ebata 2011). The landscape mosaic has been additionally altered by extensive salvage logging, road building, and new conifer plantations.

Previous Studies on Fuels and Fire Behaviour Following Mountain Pine Beetle Attack

Since the beginning of the outbreak, managers and researchers have been concerned about heightened fire hazard in affected areas. Following MPB attack, needles turn from green to red over a period of approximately 1 year (Jolly *et al.* 2012a), by which time their foliar moisture content can drop to 10% to 12% or lower (Jolly *et al.* 2012a, Page *et al.*

2013). Dead needles typically remain in tree crowns in British Columbia for approximately 2 to 3 years following attack (Wulder *et al.* 2006). With reduced light and wind interception, remaining branches and stems become rapidly desiccated, in-stand wind speed increases, and increased sunlight promotes rapid drying of surface fuels. Managers and researchers have often assumed that fuel conditions during these early stages following beetle kill would induce crowning at lower fire intensity levels and lead to more rapidly spreading crown fires, compared with healthy pine stands (e.g., Romme *et al.* 2006). An earlier generation of research on fuels and fire danger, though lacking data or validation, identified forest areas with dead trees and dense, dead foliage as the highest category of crown fire hazard (Fahnestock 1970). In British Columbia, anecdotal reports from fire suppression crews and fire behaviour specialists suggested that personnel were frequently surprised by the rapid spread and high intensity of fires spreading in red-attack pine stands (B. Armitage, Ember Research Services, personal communication, 2004; M. Pritchard, British Columbia Ministry of Forests and Range, personal communication 2010; Wildfire Management Branch, British Columbia Ministry of Forest and Range, unpublished field reports, 2002-2010). However, these hypotheses and observations had not been tested or quantified before now, and there are very few aids available for fire behaviour forecasting and planning in large areas of beetle-killed pine fuels.

Several recent studies have used models to simulate the effects of MPB attack on fuels succession and fire behaviour potential in the western US (e.g., Page and Jenkins 2007, Jenkins *et al.* 2008, Simard *et al.* 2011, Hoffman *et al.* 2012). However, the findings of these studies have been mixed and difficult to verify, often due to the shortcomings and uncertainties associated with the models used. Jolly *et al.* (2012a) noted that there is a “virtual void” of evidence to test the many model predic-

tions. To our knowledge, no observations have been made or experiments conducted on fire behaviour in variable burning conditions in recently killed MPB-affected stands that would permit the testing of physical models or development of empirical models.

Empirical Models for Fire Spread Prediction

The objectives of this study were to review documented fire behaviour observations in early post-MPB attacked stands in British Columbia, and to provide a first approximation model of fire spread in recently dead lodgepole pine for managers and researchers. Most fire spread models in current use incorporate physical principles as well as empirically derived constants and assumptions. Some models include detailed parameterization of fuel properties in forest stands and use this structural basis for modeling fire spread using physical or empirical approaches (e.g., Rothermel 1972, Linn *et al.* 2002, Cruz *et al.* 2005). An alternative method involves developing empirical models from experimental and observational data in commonly encountered fuel types, as is done in the Canadian Forest Fire Behavior Prediction (FBP) System, a sub-component of the Canadian Forest Fire Danger Rating System (CFFDRS; Stocks *et al.* 1989). In the latter approach, structural attributes that affect fire behaviour are implicit in fuel complexes that are broadly defined by dominant tree species, qualitative forest floor characteristics, and a few simple structural attributes (Forestry Canada Fire Danger Group 1992 [hereafter FCFDG 1992], Taylor *et al.* 1997). Some of the forest fuel complexes that are defined in the system and relevant to the present study include C-3 (mature jack or lodgepole pine), M-3 (dead balsam fir [*Abies balsamea*

L. {Mill.}] mixedwood-leafless) and C-2 (boreal spruce [*Picea mariana* {Mill.} B.S.P. and *Picea glauca* {Moench} Voss]; FCFDG 1992). The FBP System framework has been effective for fire behaviour prediction across Canada, including central interior British Columbia, where large areas of forest exist with relatively homogeneous forest structure and composition (Rowe 1972). However, as has been previously noted, the overall contribution of fuels to fire behaviour in the FBP System is quite coarse compared to the influence of fire weather (Hély *et al.* 2001); the system has relatively few fuel types and very limited capabilities for adjusting fuel structure. This is an important caveat when studying MPB-killed stands, where the main distinguishing feature—the proportion and condition of dead trees—varies within and between stands and leads to increased structural heterogeneity due to variation in the timing and intensity of MPB attacks.

Importantly, using the FBP System framework for this analysis would enable experimental findings to be easily integrated with existing decision support systems in British Columbia and across Canada. We posited that spread observations obtained from MPB-affected stands could be readily compared with predictions from the FBP System, using the C-3 fuel type¹, which represents the fuel structure of healthy green pine stands. The C-3 fuel type equations were developed from several decades of experimental fire and wildfire observations obtained over a range of weather conditions in lodgepole and jack pine stands across Canada (Lawson 1973, Quintilio *et al.* 1977, Stocks 1989). Comparing the spread rates of fires in MPB-affected stands with the predictions of the C-3 model would demonstrate the effect of MPB attack on wildfire

¹The C-3 model is defined as: “pure, fully stocked (1000 to 2000 stems ha⁻¹) jack pine or lodgepole pine stands that have matured at least to the stage of complete crown closure. The base of live crown is well above the ground. Dead surface fuels are light and scattered. Ground cover is feather moss (*Pleurozium schreberi* or similar species) over a moderately deep (approximately 10 cm), compacted organic layer. A sparse conifer understory may be present.” (Forestry Canada Fire Danger Group 1992: 14).

spread. The MPB-attack observations could then be used to build a new spread model, should the difference be significant.

METHODS

Study Area and Spread Measurements

Fire spread observations were obtained from experimental fires and wildfires that fol-

lowed MPB outbreaks in pine-dominated forests across interior British Columbia. The majority of fires occurred on the Nechako and Chilcotin plateaux (Figure 1), forested landscapes of broad rolling hills and ridges dominated by lodgepole pine. This was the most severely affected region in the current MPB outbreak (Westfall and Ebata 2011). We began this study by carrying out experimental fires under carefully measured environmental con-

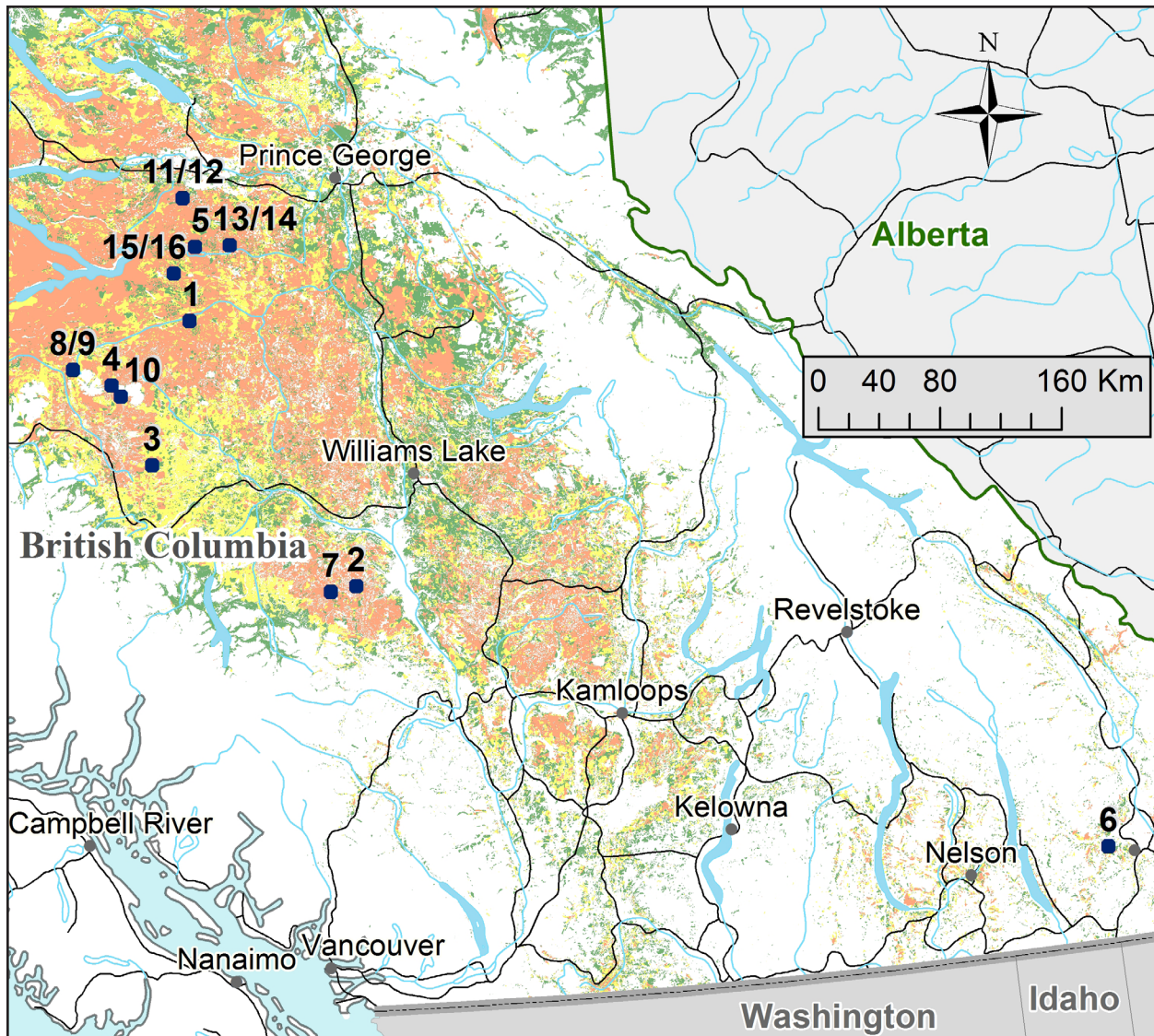


Figure 1. Overview map of the studied fire locations and recently mapped mountain pine beetle (MPB) outbreak in British Columbia, Canada. Numbers represent studied fire observations. Green, yellow, and red shading represents light, moderate, and severe and very severe MPB attack levels, respectively, as surveyed at the stand polygon level between 1999 and 2007 from provincial databases (see Van Sickle *et al.* 2001 and Taylor *et al.* 2006 for details).

ditions at the Carrot Lake research site (described below); however, expediency required that most observations be obtained indirectly from wildfires. Thus, spread rates were obtained from 11 wildfires and 2 experimental fires. Three of the wildfires each yielded two independent rate of spread (ROS) measurements, for a total dataset of 16 ROS observations. Candidate fires were carefully selected to be in closed stands dominated by mature lodgepole pine, and thus representative of the C-3 FBP fuel type prior to MPB attack. In general, the method used to record ROS on all fires was simply to measure the position of the fire front at different times (as per Alexander and Thomas 2003).

The majority of the ROS observations in MPB-affected stands were obtained by interpreting oblique aerial photographs taken by staff of the British Columbia Wildfire Management Provincial Air Tanker Centre (PATC). From an archive of over 3000 fires photographed by PATC between 2000 and 2012, a small proportion (<5%) of fires were identified in which the position of the head could be located in two or more successive photographs within a relatively homogeneous fuel type. A final subset of 10 fires was found that occurred in stands composed of more than 50% recent MPB-affected lodgepole pine, and for which the time-sequenced photographs also captured key geographic reference points (e.g., roads, water bodies, harvested blocks, or forest openings) that could be used to estimate the position of the fire front with reasonable precision (~10 m to 50 m). Photographs were captured prior to effective suppression activities and therefore represented free-burning conditions (Figure 2A through 2C). The distance between successive fire front positions was then measured after transferring them to imagery in Google Earth (Google Inc., Mountain View, California, USA; GE), as described below.

The photographic interpretation of headfire positions, a subjective process, was performed by an individual with several decades of ex-

perience in fire behaviour (author R. Lanoville), and done independently from the fire weather analysis. The steps for interpreting each photo pair were as follows (Figure 2C):

1. rapidly examine photos by fire file for likely candidates (apparent fuel type match, headfire visible, landscape features visible in multiple photographs);
2. locate approximate fire position in GE based on final perimeter polygon, confirm landscape features in available imagery;
3. manipulate GE imagery to match view of photograph based on landscape features;
4. overlay positions of headfire to GE based on visible location in photos;
5. measure spread distance between successive fire front positions (P) representing the position at different times;
6. use time stamps (T) on image files to determine the duration between fire front positions in minutes and seconds, and calculate ROS as

$$ROS = \frac{(P_2 - P_1)}{(T_2 - T_1)} \quad (1)$$

A final step involved verifying the stand composition from forest inventory and final fire perimeter data, and eliminating fires that did not match the stand characteristics of interest (recently attacked MPB-affected lodgepole pine). Although simple in concept, the photo interpretation procedure was very challenging and time consuming to implement. The spread measures derived this way are likely less accurate than direct observation and measurement using global positioning systems (GPS) or *in situ* ROS timers used in the other fire observations in this study.

As a partial test of concept, ROS from two additional wildfires that occurred in non-MPB affected fuels were analyzed in a similar manner. These data points were not part of the

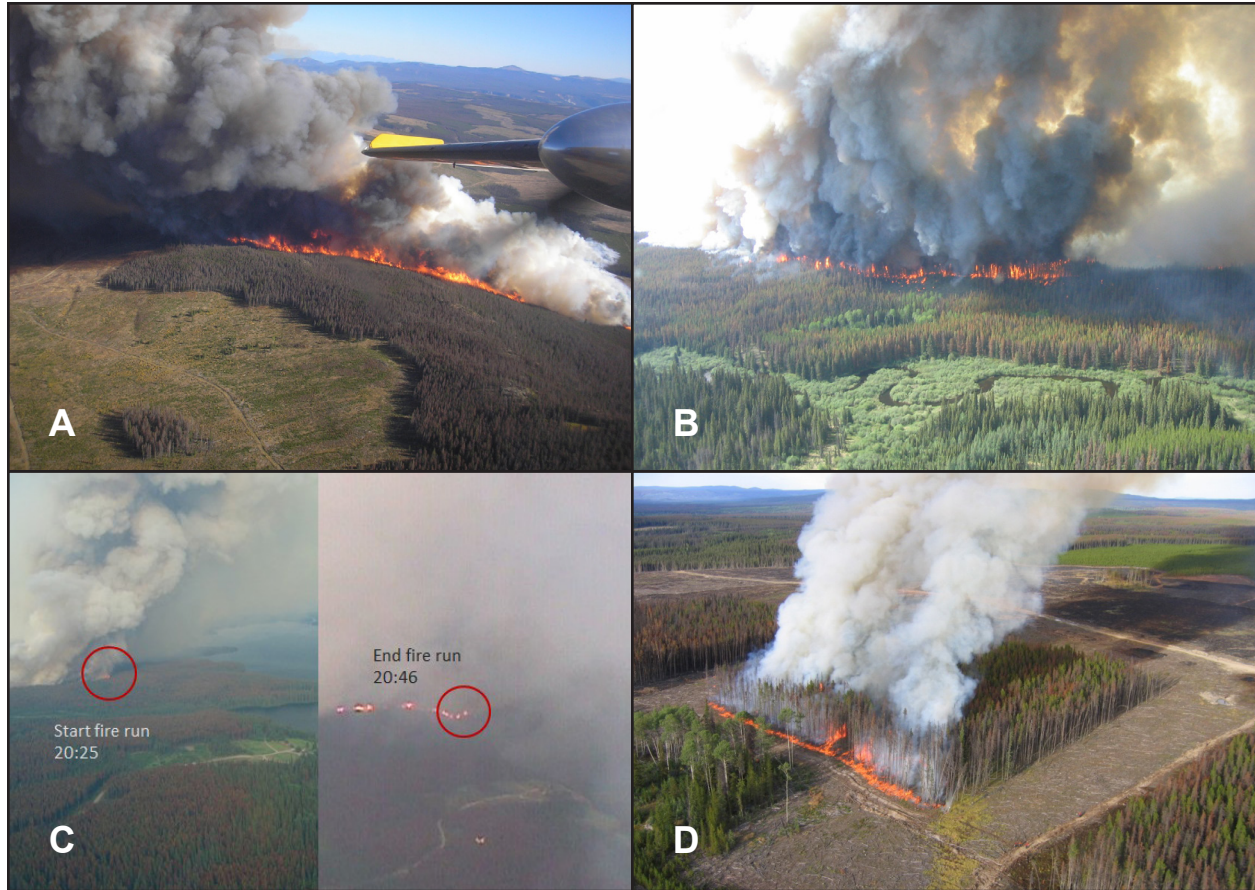


Figure 2. Oblique aerial photographs of four of the studied fires: (A) active crown fire behaviour during a 2009 wildfire burning in early grey-attack pine fuels (Figure 1: site 2); (B) active crown fire behaviour during a 2005 wildfire, burning in red-attack pine during the height of the MPB outbreak (Figure 1: site 13); (C) example of a photo pair used to derive spread rate for a 2004 wildfire in red-attack pine, showing active crown fire (Figure 1: site 5); and (D) surface fire behaviour during the 2006 Carrot Lake experimental burning project (Figure 1: site 16). Crown fire behaviour was observed in the majority of the studied fires, even in grey-attack stands that had lost most crown foliage.

MPB-killed pine dataset, but were compared to predicted ROS from standard FBP fuel types. This served as a partial verification of the photo-interpretation procedure.

Three wildfire observations in MPB-affected stands were obtained by experienced observers who were directly monitoring fire behaviour during the course of fire management operations. The observers (author D. Hicks and S. Harvey, Ministry of Forests and Range, Prince George, British Columbia, Canada), flew in helicopters over active fires and measured fire front positions using handheld GPS devices at successive times. The accuracy of

the measurements on these two directly observed fires (both ROS and fire weather values) was likely greater than the estimates produced via photo-interpretation, as the fire spread distance and local weather at the time of burning were confirmed by the field observers.

Two fire spread observations were obtained from experimental burns. The experimental installation (Carrot Lake [CL hereafter]; Lavoie *et al.* 2006) consisted of a series of 4 ha plots that had been established prior to, and in anticipation of, MPB spread into the local area (approximately 90 km south of Vanderhoof, British Columbia, Canada). Experi-

mental plots were ignited in early August 2006, using line ignition from handheld drip torches at the windward edge (Figure 2D). In each plot, the time of fire arrival was recorded at each point in a uniform 15 m grid using thermocouple timers (WREN Systems, Victoria, British Columbia, Canada). Fire spread rate and direction were calculated from the fire arrival and location data by triangulation (Simard *et al.* 1984). Since this method yielded numerous measures of ROS, the final ROS value used for analysis was the median of individual triangulated ROS measurements within each plot. Median values were used to reduce the influence of one or two much higher ROS measurements obtained at the plot edges due to wind exposure.

For each ROS observation in the dataset, the type of fire was noted based on visible behaviour in photographs or directly observed fire behaviour: surface fire, intermittent crown fire (also known as passive crown fire), or active crown fire (CIFFC 2003). For this purpose, active crown fire behaviour was defined as that having flame heights visibly higher than the tops of canopy trees, and the flames formed a continuous front in the fuel complex.

Fuel Conditions

Tree species composition on wildfires was determined from provincial forest inventory data (British Columbia Ministry of Forests, Lands, and Natural Resource Operations, Vegetation Resource Inventory Program; see <http://www.for.gov.bc.ca/hts/vridata/>) corroborated by visual estimates and photographs. Forest inventory polygons are derived from air photo interpretation, limited ground-truthing, and projection modeling to estimate stand characteristics (including canopy tree heights) many years after surveys based on site index and growth curves. Average tree heights on wildfires were estimated from projected heights selected from forest inventory polygons within mapped fire perimeters. Addition-

ally, on the two CL experimental fires, the species composition and condition of overstory trees greater than 7 cm diameter were assessed in experimental plots prior to burning using standard point-centered quarter (PCQ) methods (Elzinga *et al.* 2001), with 25 point locations arranged in a grid across each plot.

The year or years of peak MPB attack prior to wildfire were determined by overlaying fire polygons on provincial aerial pest survey MPB-outbreak data (details in Westfall and Ebata 2011). Year of attack in such surveys (green attack) was noted the following year once the crowns had turned red. Thus, the overall MPB-attack stage at the time of burning was estimated based on time since peak red-attack stage: red (1 to 2 years) or early grey (3 to 5 years; as per Wulder *et al.* 2006). For each wildfire, the proportion of red and grey attack in the burned stands was then estimated from the survey data, corroborated by photographs and field reports. Although it was not possible to establish the exact severity of MPB attacks at the time of fire occurrence, all fires studied burned in stands that had more than 50% of overstory lodgepole pine trees killed, based on the previous 3 years of aerial surveys.

Fire Weather

Fire weather in this study was analyzed using the indices and conventions of the Canadian Forest Fire Weather Index (FWI) System, another sub-component of the CFFDRS (Van Wagner 1987). For all wildfires, hourly observations of temperature, relative humidity, wind speed, wind direction, and precipitation were obtained to calculate FWI indices. Weather observations were obtained from the nearest representative weather station in the British Columbia Wildfire Management Branch (WMB) weather network. The WMB network stations record instantaneous weather observations on each hour, excepting wind speed, which is a 10-minute average reading

immediately before each hour, and rain is recorded as that which accumulated during the preceding hour. At the CL experimental site, weather observations were similarly recorded by an on-site station, except wind speed and direction, which were logged at 2 minute intervals.

For both wildfires and experimental fires, a single mean wind speed was calculated for the spread period corresponding to each ROS observation. For wildfires, we interpolated hourly Fine Fuel Moisture Code (FFMC; Van Wagner 1977c) and wind speed from observations to the midpoint of the spread period (in minutes); these were used to calculate the Initial Spread Index (ISI; Van Wagner 1987):

$$ISI = 0.208e^{0.05039W} \times 91.9e^{-0.138m} \times \left[1 + \frac{m^{5.31}}{4.93 \times 10^7} \right] \quad (2)$$

where W is wind speed in km h^{-1} and m is fine dead fuel moisture in percent of dry weight². For fires burning on slopes greater than 5%, the ISI slope adjustment was also calculated, based on the slope function described in the FBP System (FCFDG 1992). The net vectored effective wind speed and ISI were calculated using Behave 5.0 Professional (Remsoft, Fredericton, New Brunswick, Canada). Fire weather calculations for wildfires were conducted after ROS calculations, and by different individuals (authors D. Perrakis and S. Taylor) to avoid bias. After wind speed and ISI measures were calculated for each fire observation, the appropriate photographs were examined to ensure consistency in terms of smoke column characteristics. For the two CL experimental fires, ISI was calculated using

the mean wind speed (measured at 1 min intervals) as the flaming front traversed the plot, as described above.

Fitting Rate of Spread Curves

Initially, we used a similar procedure to model ROS in dead pine fires as was used for the conifer fuel types in the FBP System. Models employ the three-parameter Chapman-Richards growth equation (Richards 1959):

$$ROS = a \times (1 - e^{-b \times ISI})^c, \quad (3)$$

which passes through the origin and has a sigmoidal form. The terms a , b , and c in Equation 2 are shape parameters; a is described as the “levelling-off function” (FCFDG 1992), and represents the asymptote of the curve and the maximum possible ROS value associated with each fuel type, nearly reached at very high ISI values. In the 1992 FBP System the a and c parameters for most conifer fuel types were assigned based on the authors’ expert opinion and visual inspection, and the b parameter was the maximum likelihood fit estimate (T. Lynham and B.J. Stocks (retired), Natural Resources Canada, Canadian Forest Service, personal communication). For the C-3 fuel model, the parameters were set to $a = 110$ and $c = 3$; for C-2, $a = 110$ and $c = 1.5$ (FCFDG 1992); for the M-3 fuel model (recently updated to fix certain inconsistencies), $a = 120$ and $c = 1.4$ (Wotton *et al.* 2009).

In the present study, we fit several models to the MPB-fire data based on the form of Equation 2. Following the FBP System con-

²In the Canadian Forest Fire Danger Rating System, fine dead fuel moisture is estimated based on measured weather conditions using the Fine Fuel Moisture Code (FFMC). The FFMC converts hourly or daily readings of temperature, relative humidity, wind speed, and precipitation into dimensionless FFMC values. The conversion is based on empirical functions investigated in field conditions designed to simulate conditions in pine litter beds, originally investigated in jack pine stands in Ontario, Canada. Indices such as the FFMC act as a form of bookkeeping system that model the continuous changes to fuel moisture in the absence or presence of precipitation.

vention and similar to the M-3 fuel type, the a parameter³ was fixed ($a = 120$) in all models, representing a maximum possible ROS of 120 m min⁻¹. The b and c parameters were assigned or fit to the data in various iterations, and several diagnostics were used to compare the different models. In addition, we used several forms of logistic regression to test the relationship between ISI and fire type (surface or crown fires; intermittent crown fires were classed as crown fires for this test) and identify the most likely crowning threshold. Non-linear regressions were performed in R 2.13.2 (R-Project for Statistical Computing; <http://r-project.org>) using the *nls* model function (non-linear least squares regression). Logistic regression analyses (maximum likelihood, exact, Bayesian) were carried out using procedures in SAS 9.2 (SAS Institute Inc., Cary, North Carolina, USA).

RESULTS

Fuel Characteristics

The overstory stand composition estimated from inventory data and burned in the wildfires (Table 1: observations 1 to 14) consisted of 60% to 100% mature lodgepole pine (~90 yr to 160 yr old; PICO); secondary canopy species included subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.; ABLA) and interior spruce (*Picea glauca* [Moench] Voss x *P. engelmannii* [Parry ex Engelm.]; PIGX). Time since peak MPB attack varied between about 1 yr and approximately 5 yr, corresponding to epidemic conditions (as per Jenkins *et al.* 2008), or the red-attack and early grey-attack stages. Based on the interpreted inventory data and model-

ing, canopy trees (estimated stand averages) were between 16 m and 22 m in height (Table 1: observations 1 to 14). No other canopy fuel information was available for these stands.

For the two plots burned at the Carrot Lake experimental site, the overstory was composed of 76% to 89% PICO, 2% to 12% PIGX, and 2% to 12% ABLA. Mean overstory tree heights (and standard deviations) based on PCQ sampling were 16.3 m (5.0 m) and 15.0 m (4.3 m) in the two plots, respectively; canopy base height values (and stand deviations) in the two plots were 9.8 m (4.8 m) and 9.6 m (4.0 m), respectively (Table 1: observations 15 to 16). The main MPB attack at the experimental site (noted in aerial surveys and confirmed by ocular estimates in person) occurred in 2004 to 2005, one to two years before plots were burned in early August 2006. The lodgepole pine components in both plots contained a mix of attack stages prior to burning: in Plot 1 (Table 1: observation 15), 17%, 36%, and 47% of trees were in green, red (some needles remaining), and grey (no needles remaining) stages, respectively, excluding older snags; the proportions in Plot 3 (Table 1: observation 16) were 23%, 33%, and 44% in green, red, and grey stages, respectively, excluding old snags.

Stand composition preceding fires at all locations was very similar to previously described studies on MPB outbreaks (Cole and Amman 1980) and post-MPB fire behaviour (Page and Jenkins 2007). Prior to MPB attack, all stands would likely have been a good to fair fit with the FBP C-3 fuel model (Taylor *et al.* 1997).

³The a parameter value in the FBP ROS models is typically assigned based on expert opinion rather than rigorous scientific basis. Wotton *et al.* (2009) describe several examples since the original FBP System publication (Forestry Canada Fire Danger Group 1992) where ROS values were measured that surpassed the a parameter for the particular fuel type. This included a wildfire in an Australian pine plantation spreading at 200 m min⁻¹ under some of the most extreme conditions ever recorded (ISI 175, BUI 199). Measurements of ROS tend to be less accurate under extreme conditions due to the extreme safety hazards these conditions create, as well as the increasing influence of highly stochastic processes such as spotting (ember lofting) and atmospheric instability. As a result, the accuracy of the upper region of these ROS models is clearly low and inherently difficult to verify.

Table 1. Summary of fire observations and stand characteristics classified by monitoring method.

Monitoring method	Observation number	Fire year	Stand composition ^a	Canopy height (~m) ^b	MPB attack stages (Overall category) ^c	Year(s) since peak MPB ^d
Photo interpretation (wildfires)	1	2009	PICO: 80 PIGX: 20	18.9	Gy, Gn (Gy)	4 to 5
	2	2009	PICO: 95 PIGX: 5	16.6	Gy (Gy)	3 to 4
	3	2009	PICO: 100	16.1	Gy, R, Gn (Gy)	3 to 4
	4	2008	PICO: 100	16.0	R, Gn (R) ^e	2 to 3 ^e
	5	2004	PICO: 100	19.8	R (R)	1
	6	2008	PICO: 90 ABLA: 10	21.4	Gn, R (R)	1 to 2
	7	2007	PICO: 100	17.7	R (R)	1
	8 [†]	2006	PICO: 70 PIGX: 30	19.3	R (R)	1
	9 [†]	2006	PICO: 60 PIGX/ABLA: 40	19.3	R (R)	1
	10	2009	PICO: 90 PIGX: 10	16.9	Gy, R (Gy)	4
	11 [‡]	2010	PICO: 90 PIGX: 10	22.0	Gy (Gy)	5
Direct measurement (wildfires)	12 [‡]	2010	PICO: 80 PIGX: 20	22.0	Gy (Gy)	5
	13 [§]	2005	PICO: 100	21.2	R, Gy (R)	1
	14 [§]	2005	PICO: 100	21.2	R, Gy (R)	1
Experimental burns	15	2006	PICO: 76 ABLA: 12 PIGX: 12	21.7	Gy, R, Gn (R)	1
	16	2006	PICO: 89 PIGX: 9 ABLA: 2	21.7	Gy, R, Gn (R)	1

^a Acronyms designate tree species: PICO = lodgepole pine; ABLA = subalpine fir; PIGX = interior spruce.

^b Average height of canopy, based on estimates from projected forest inventory; see text for details.

^c MPB attack stage category symbols, listed in order of decreasing importance: Gn = green-attack or live green; R = red-attack; Gy = early grey-attack; overall category is based on time since attack—R: 1 yr to 2 yr; Gy: 3 yr to 5 yr.

^d Number of years since peak mountain pine beetle attack in stand, estimated based on aerial detection.

^e Based on estimated peak year of MPB attack, fire observation 4 was on the borderline between red- and early grey-attack categories; it was assigned to the red-attack group based on the visual appearance of the canopy in photographs (abundant red trees still visible).

^{†,‡,§} Symbols indicate pairs of observations from one single fire event; see text for details.

Fire Behaviour Observations

Fire weather and fire behaviour characteristics of the 16 fire observations are shown in Table 1, arranged by data collection method: (1) photographic interpretation of wildfire spread, (2) direct (airborne) measurement of wildfire spread using GPS, or (3) ground measurement of spread rate during experimental burns (Table 1: observations 1 to 11, 12 to 14, and 15 to 16, respectively). Ten observations (1 to 7, 10, and 15 to 16) were from independent wildfires or experimental burns. Three additional wildfires were large, land-

scape-scale events that each provided two separate fire run observations (Table 1: observations 8 to 9, 11 to 12, and 13 to 14). All six of these observations were treated as independent data points based on several factors: the measured spread events were either non-adjacent in time and space (observations 8 to 9 and 11 to 12; each of these observations was measured on a different day with independent starting and ending positions) or very long in duration (observations 13 to 14, observed consecutively, were 182 and 169 minutes in duration, from 14:39 to 17:41 and 17:41 to 20:30, respectively). These long runs (observation 13: 4.3 km;

observation 14: 3.3 km) covered large areas of forest and incorporated fluctuating weather conditions and heterogeneous fuel structure and composition along the way.

The study fires exhibited much higher ROS and much more frequent crown fire behaviour compared to predictions from the C-3 fuel type model that represent unattacked stands (Table 2). There were no obvious differences in fire behaviour between red-attack (1 yr to 2 yr since peak MPB) and early grey-attack (3 yr to 5 yr since peak MPB) stands. Crown fires (intermittent or active)

were observed in both stages of MPB attacks, and neither stage clearly produced either faster or slower fire spread (Figure 3). Rates of spread varied between 2.6 m min⁻¹ and 66.0 m min⁻¹, and included 2 surface fires, 2 intermittent crown fires, and 12 active crown fire observations. Associated hourly ISI values ranged between 4.7 and 21.2. The C-3 fuel type predicted that 8 of the 16 fires would be surface fires, 7 of 16 would be intermittent crown fires, and only 1 would be an active crown fire under similar fire weather (ISI) conditions (Table 2). The duration of the observed

Table 2. Summary of fire environment and fire behaviour measurements for the 16 monitored fire runs.

Observation number ^a	FFMC ^b	WS ^b (km h ⁻¹)	Adjusted ISI ^{b,c}	BUI ^b	Duration of Observed fire spread (min)	ROS ^b (m min ⁻¹)	Predicted C-3 fire type ^d	Observed fire type ^d	Wx stn ^b distance (km)
1	91.3	11.3	10.5	65	75	16.6	IC	AC	31
2	91.0	26.1	21.2*	128	14	66.0	AC	AC	11
3	92.6	10.1	10.3	141	5	32.7	IC	AC	40
4	90.3	15.5	9.7	62	26	12.5	S	AC	39
5	90.0	10.0 ^e	7.1	85	21	30.6	S	AC	27
6	93.2	4.1	8.6*	100	12	15.9	S	AC	14
7	87.8	19.5	8.4	78	3	29.7	S	AC	25
8	90.6	10.1	7.8	93	107	22.3	S	AC	5
9	92.5	9.3	9.8	93	3	28.9	IC	AC	5
10	89.2	7.7	5.0*	81	85	8.1	S	IC	32
11	93.0	14.2	13.4	81	22	19.1	IC	AC	28
12	93.0	14.5	12.1	79	74	13.5	IC	IC	28
13	92.4	11.0	10.6	88	182	23.8	IC	AC	25
14	92.0	10.2	9.6	88	169	19.4	IC	AC	25
15	87.0	10.0	4.7	70	22	2.7	S	S	0.7
16	90.0	11.0	6.5	111	35	2.6	S	S	0.7

^a Observation numbers match fire observation numbers in Table 1.

^b Acronyms follow Fire Weather Index System convention: FFMC = Fine Fuel Moisture Code; WS = wind speed; ISI = Initial Spread Index; BUI = Buildup Index (Van Wagner 1987). Wx stn = weather station.

^c Asterisks (*) indicate fires where ground slope was >5%; for these, wind speeds were adjusted based on vectored slope steepness and aspect to yield adjusted ISI (using C-3 fuel type values), as per Van Wagner (1977b).

^d Predicted fire type was calculated using the FBP default foliar moisture content of 97%. S indicates surface fire behaviour (<0.1 crown fraction burned, or CFB), IC indicates intermittent crown fire (0.1 ≤ CFB ≤ 0.9), and AC indicates active crown fire behaviour (>0.9 CFB), as per Forestry Canada Fire Danger Group (1992).

^e Wind speed on fire observation number 5 was inconsistent between nearby weather stations, and did not match with the smoke column characteristics and direction; 10 km h⁻¹ was estimated based on smoke column appearance and fire reports.

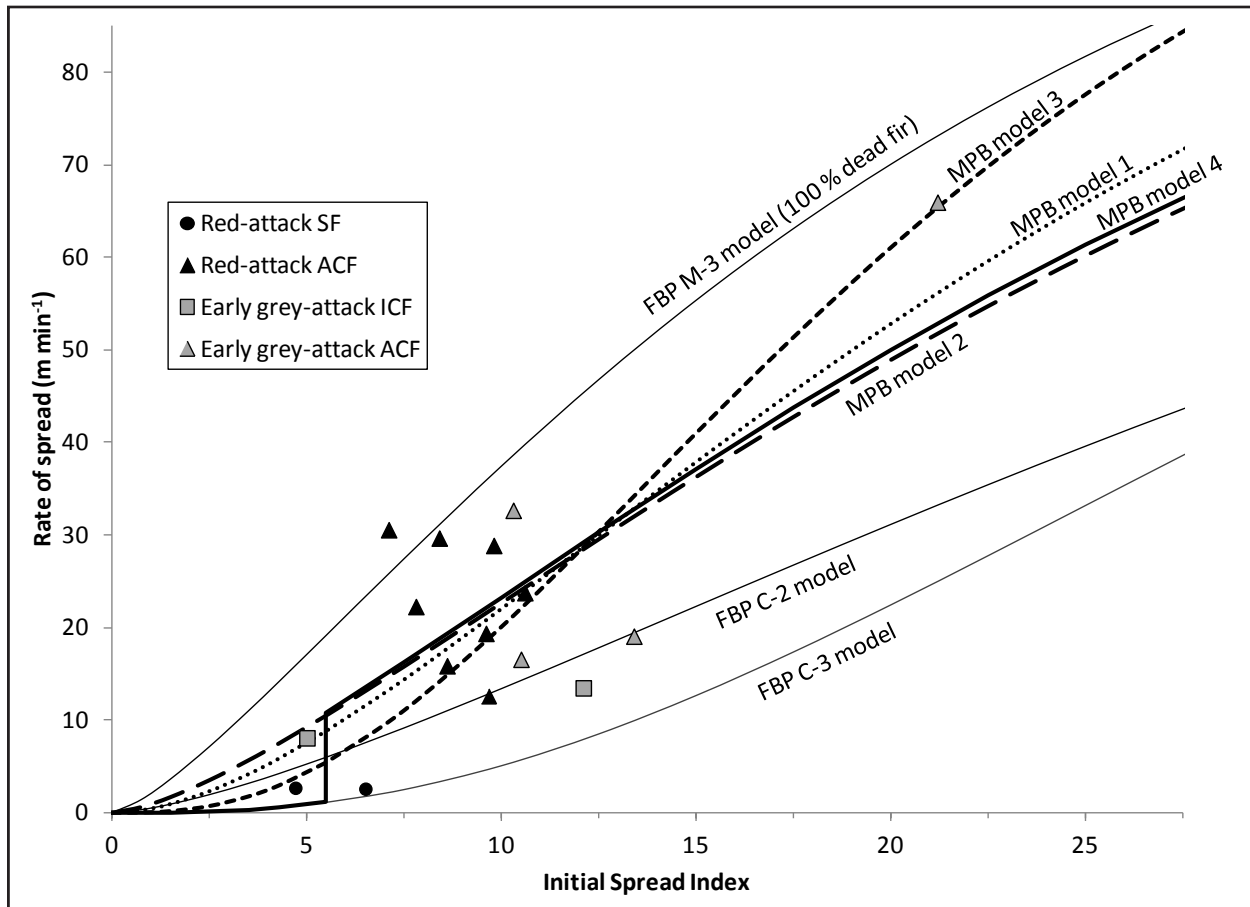


Figure 3. ISI-ROS scatter plot showing the 16 fire observations and the four fitted ROS models. Curves for FBP fuel type models C-2 (boreal spruce), C-3 (mature jack or lodgepole pine) and M-3 (dead balsam fir-leafless with 100% dead fir) are shown for comparison purposes (calculated from Forestry Canada Fire Danger Group 1992, Wotton *et al.* 2009). Abbreviations are defined as follows: red-attack: 1 to 2 years since beetle attack; early grey-attack: 3 to 5 years since beetle attack; SF: surface fires; ICF: intermittent crown fires; ACF: active crown fires; see text for further details.

runs ranged between approximately 3 min and 182 min in length, with an average length of 49 min. Weather stations were between about 5 km and 40 km distant from the associated fire locations, with the exception of the CL experimental site, where the station was less than 1 km from burn plots (Table 2: observations 15 to 16).

Fire Type and Crowning Probability

Rates of spread of the 16 observations were 2.6 m min⁻¹ and 2.7 m min⁻¹ (ISI 6.5, 4.7) for surface fires, 8.1 m min⁻¹ to 13.5 m min⁻¹ (ISI 5.0 to 12.1) for intermittent crown fires,

and 12.5 m min⁻¹ to 66.0 m min⁻¹ (ISI 7.1 to 21.2) for active crown fires. In order to identify the threshold ISI for crown fire initiation, we used several techniques related to logistic regression. There is a strong relationship between ISI and the probability of crowning in the FBP System ROS models. In order to provide a reference for comparing with MPB-affected stands, we first used the raw data used to build the C-3 FBP model (24 surface fires and 34 crown fires; M. Wotton, Natural Resources Canada, Great Lakes Forestry Centre, personal communication) to fit a logistic regression model of probability of active crown fire as a function of ISI, using maximum like-

likelihood estimate (MLE) methods. This model based on the C-3 dataset was highly significant (intercept: $\beta_0 = -9.5503$, $P < 0.001$; ISI: $\beta_1 = 0.9538$, $P < 0.001$). For MPB affected stands, we initially used MLE methods to estimate logistic model parameters, but found a non-significant relationship between ISI and crowning (intercept: $\beta_0 = -6.218$, $P = 0.164$; ISI: $\beta_1 = 1.114$, $P = 0.109$), likely due to the small sample size. Secondly, we used exact logistic regression, recommended for small sample sizes and unbalanced datasets (Mehta and Patel 1995). While the exact analysis indicated a significant relationship between ISI and crowning in MPB affected stands ($P = 0.030$), our data were too sparse to estimate both the slope and intercept parameters using exact methods. Lastly, we exploited the information from the C-3 analyses by using the C-3 MLE logistic model parameter estimates as priors, and applying Bayesian methods (Sullivan and Greenland 2013) to estimate the posterior logistic model parameters (intercept: $\beta_0 = 7.272$, standard deviation = 3.426; ISI: $\beta_1 = 1.337$, standard deviation = 0.550; 21 000 iterations). The Bayesian logistic model indicated a 50% probability of crowning, interpreted as the crowning threshold, at ISI 5.5 (25th through 75th percentile range 2.9 to 10.1).

Fitting Rate of Spread Models

We tested four sets of parameters in Equation 2 to predict ROS (Table 3). In Model 1, b and c were both fit to the data, and were both significantly different from zero ($\alpha = 0.05$). In models 2 and 3, only b was fit to the data, and c was fixed, as follows (FCFDG 1992, Wotton *et al.* 2009): Model 2: $c = 1.5$ (as per the C-2 FBP fuel model); Model 3: $c = 3$ (as per the C-3 FBP fuel type model). Model 4 was a hybrid model for which we assumed that surface fires followed the left side of the FBP C-3 function, and fit a curve to the 14 crown fire observations alone representing crown fire spread (Model 4c: $c = 1.5$). The instantaneous

transition to crown fire in Model 4 was assumed to occur at the crown fire initiation threshold of ISI 5.5 (from the logistic regression analyses) following the dual equilibrium ROS concept (Van Wagner 1993, Cruz *et al.* 2008). Coefficients of determination (r^2) and Akaike's Information Criterion (AIC) values for all four models are quite similar, reflecting the very similar model forms tested. Based on r^2 , Model 1 is slightly preferred over the others, although Model 4 may reflect the effects of crowning (rapid increase in ROS above the crowning threshold) more accurately. Cook's distance (Cook's D) values in regression models combine the residuals and the leverage of individual data points in order to identify highly influential points or areas with sparse observations (Cook and Weisberg 1982). High values of Cook's D are those with a value greater than $4/n$ (Bollen and Jackman 1990), which in the present case is 0.25 for models 1 to 3 and 0.286 for Model 4 (Table 3). As is apparent from Figure 3, observation #2 is highly influential in models 1, 2, and 4 due to its high leverage, while observations #12 and #13 are particularly influential in Model 3 due to their large residuals.

The ISI-ROS graphs for the four models as well as the spread of individual fire observations are illustrated in Figure 3. Curves showing ISI-ROS relationships for FBP fuel types C-2, C-3, and M-3 (100% dead balsam fir) are also shown for comparison (calculated from FCFDG 1992 and Wotton *et al.* 2009). The ROS observations in MPB-affected stands were all located above the C-3 line, indicating faster ROS than would be predicted by the C-3 model; most observations were also located above the C-2 line. Nearly all of the observations were located below the M-3 (100% dead fir) model (Figure 3), which has the highest ROS of the conifer types in the FBP System.

The relationship between observed and predicted ROS for the 16 fire runs is shown in Figure 4. Based on Model 1, observed ROS was approximately 2.67 times faster than ROS

Table 3. Summary statistics from the fitted ROS models, based on Equation 2.

	Model 1	P	Model 2	P	Model 3	P	Model 4c	P	Model 4
<i>a</i>	120		120		120		120		^a
<i>b</i>	0.0518 [†]	0.025	0.0399 [†]	<0.001	0.0801 [†]	<0.001	0.0408 [†]	<0.001	^a
<i>c</i>	1.871 [†]	0.0143	1.5		3		1.5		^a
n	16		16		16		14		16
r ²	0.572		0.563		0.515				0.557
AIC ^b	76.716		75.024		76.718				75.204
Obs. ^c	Cook's D	Infl.?^d	Cook's D	Infl.?^d	Cook's D	Infl.?^d	Cook's D	Infl.?^d	
1	0.0226		0.0452		0.0264		0.0544		
2	3.4167	*	0.6976	*	0.0012		0.6031	*	
3	0.0445		0.0654		0.1047		0.0587		
4	0.0340		0.0594		0.0277		0.0688		
5	0.1640		0.0804		0.0867		0.0786		
6	0.0016		0.0043		0.0005		0.0061		
7	0.0834		0.0628		0.0938		0.0592		
8	0.0268		0.0131		0.0309		0.0114		
9	0.0266		0.0318		0.0624		0.0274		
10	0.0001		0.0002		0.0007		0.0003		
11	0.1618		0.2287		0.4170	*	0.2631		
12	0.1335		0.2488		0.3187	*	0.2801		
13	0.0000		0.0002		0.0016		0.0011		
14	0.0009		0.0031		0.0005		0.0050		
15	0.0084		0.0039		0.0000				
16	0.0471		0.0290		0.0043				

[†] Indicates fitted coefficients (rather than assigned *a priori*).

^a Model 4 is a combination of Model 4c (for intermittent or active crown fires) and the FBP C-3 curve (for surface fires); see text for details.

^b Akaike's Information Criterion.

^c Observations numbers; they are same as in tables 1 and 2.

^d Influential observations (*) are considered those where Cook's Distance > 4/n, or 0.25 for the present case.

predicted by the FBP C-3 model ($r^2 = 0.403$). Analyzed individually, ROS observations were on average 5.2 times faster than predicted (standard deviation = 2.79) over the range of fire spread. The rates of spread of the two fires in healthy non-MPB affected conifer stands are also shown in Figure 4. The first observation was an active crown fire in a mature mix of white spruce (*Picea glauca* [Moench] Voss) and black spruce (*P. mariana* [Mill.] Britton, Sterns and Poggenb.), considered a good fit

with the C-2 fuel type (ISI 11.1; observed ROS: 15.2 m min⁻¹; C-2 predicted ROS: 15.3 m min⁻¹; predicted fire type: active crown). The second observation was from an intermittent crown fire burning in healthy mature lodgepole pine with a sub-component of interior spruce, considered a fair fit with the C-3 fuel type (ISI 8.9; observed ROS: 5.0 m min⁻¹; C-3 predicted ROS: 3.9 m min⁻¹; predicted fire type: intermittent crown).

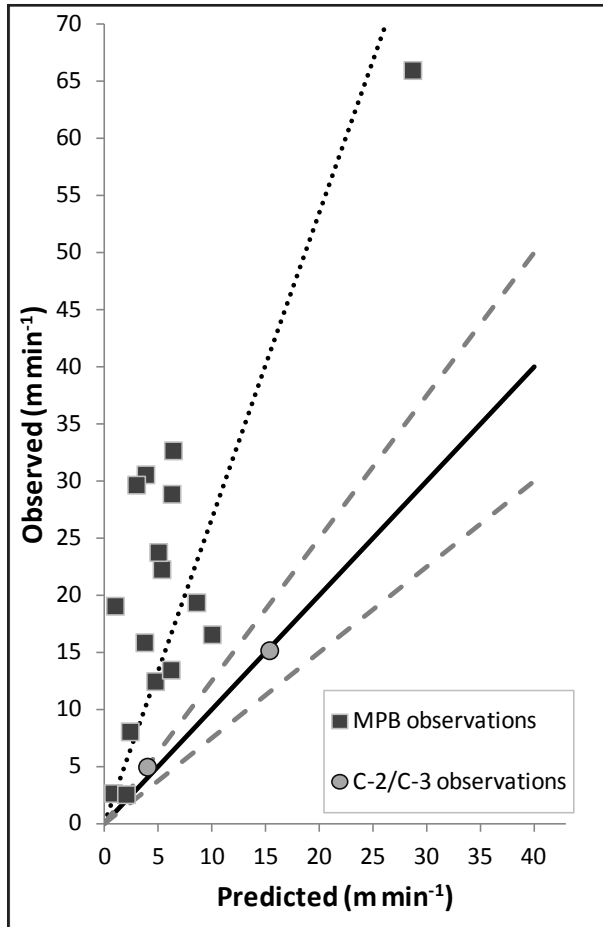


Figure 4. Observed-predicted relationship for ROS in MPB-affected stands using predictions from the C-3 (mature jack or lodgepole pine) FBP fuel type and MPB Model 1 (present study); two control fires in other conifer fuels are also shown. The solid line represents perfect agreement; dashed lines show $\pm 25\%$ confidence band.

DISCUSSION

Fuels and Fire Behaviour in Recent Beetle-Killed Lodgepole Pine

This study presents some of the first systematic observations of fire behaviour and ROS in MPB-killed lodgepole pine. We acknowledge that the data and methods are imprecise and that the models would benefit greatly from additional fire observations in this fuel type. Specifically, the wildfire data suffered from a lack of detailed fuel measure-

ments, some very short fire observation durations (Table 2: observations 3, 7, and 9), weather stations somewhat distant (in time and space) from the fire observations, and subjective (although unbiased) spread distance measurement methods. Nonetheless, these are common problems with wildfire observations and, based on at least one set of criteria (Gould *et al.* 2011), these represent relatively high quality wildfire data: weather data in this study are of rank 1 (weather station very near the fire location, or direct measurements on site) or rank 2 (weather station within 50 km of a fire). The same set of standards suggest that the fire spread data merit a ranking of between 1 (direct timing of fire spread by the authors) and 2 (reliable timing of fire spread by a third party; Gould *et al.* 2011). More importantly, the spread rate data showed a relatively consistent relationship with the ISI measure, not unlike the ISI-ROS curves of other fuel types in the FBP System. Values of the coefficient of determination (r^2) for all four models indicate that more than half of the variability in the dataset was explained. Overall, the results suggest that crowning occurs at lower fire danger conditions and that spread rates are in the order of two to three times higher than would be predicted in unaffected lodgepole pine stands.

Why did the observed fires exhibit such high rates of spread? Van Wagner (1977a) suggested that crown fire initiation requires a critical surface fire intensity that varies depending on crown fuel moisture, crown base height, temperature, and wind speed. It is plausible that crowning would occur at lower fire danger conditions if the critical surface fire intensity were reduced, such as due to lower moisture content in the needles and fine branches of MPB-killed stands. Jolly *et al.* (2012a) reported that flammability of dying foliage increases rapidly during the early post-attack stages as foliar moisture content (FMC) declines and foliar chemistry changes dynamically. Alexander and Cruz (2013) noted that Van Wagner's (1989) foliar mois-

ture effect (FME) function, which was developed from experiments on living conifers (FMC values of ~85% to 120%) would predict an approximately eight-fold increase in ROS if extrapolated to the very dry foliage in MPB-affected stands; however, extrapolating the FME function in this manner would be well beyond its intended scope as it was based on healthy green conifer foliage. The data from the present study showed some agreement ($r^2 \sim 0.4$) with a linear increase of about 2.7 times the C-3 predicted ROS—much less than an eight-fold increase, but still a very significant effect. It should be noted that the data are dominated by crown fires; therefore, this finding applies primarily to the crown fire phase. Increased foliar flammability due to reduced foliar moisture remains the most likely explanation for higher ROS in the earliest post-MPB stands in this study (≤ 1 year since attack). As such, we expect that the highest spread rates in this fuel type would occur in pure 100% red-stage lodgepole pine stands.

Several authors, including Romme *et al.* (2006) and Jenkins *et al.* (2008), have suggested that the red-attack (epidemic) stage might present a period of heightened fuel hazard due to higher fine fuel loading and reduced FMC. However, following the red-attack stage they suggested that a prolonged period of reduced fuel hazard (during the gray-attack stage) would occur as crown fuels were lost to needle fall, lessening the likelihood of crowning and the chance of active crown fire spread. Simard *et al.* (2011), using plot data collected from the Yellowstone area and simulations using the Nexus fire behaviour model (Scott 1998), also suggested that post-MPB fuel beds generally represent a reduced hazard compared with healthy lodgepole pine stands. They found that post-MPB increases in fine fuels were minor and overshadowed by losses of crown fuels during the grey (post-epidemic) stage (Simard *et al.* 2011). However, subsequent analyses (Jolly *et al.* 2012b, Moran and Cochrane 2012) suggested that Simard *et al.*

(2011) underestimated the crowning potential due to weaknesses in their modeling approach. Schoennagel *et al.* (2012) found increased surface fuels and reduced canopy bulk density following MPB attack in moderately to severely attacked stands in Colorado (red-attack and later stages) compared to unattacked stands; however, total available canopy fuel load was not significantly different between green and attacked trees, likely due to the inclusion of fine woody branch fuels into the calculations and the presence of remnant unattacked overstory pines. Fire behaviour simulations suggested that these changes may facilitate crown fire initiation at lower wind speeds in MPB-affected stands compared with green stands.

While ROS estimates in the present study show considerable variability, it is clear that crown fires can occur and spread rapidly in the first 5 years following MPB attack in lodgepole pine forests. Surprisingly, there were no obvious differences in ROS between fires in the earlier (1 to 2 years) and later (3 to 5 years) post-MPB stages of this study, although this may be a factor of the small sample size and inexact measurements. The effects of the remnant unattacked conifer overstory may also be a significant factor as most of the fire observations occurred in stands with partial (less than 100%) overstory mortality (Table 1). The fires in early grey-attack stands, in particular, may have been influenced by the small proportion of interior spruce trees and remnant live green pines (Table 1) contributing to ladder fuels and canopy bulk density, helping bridge the crown fuels sufficiently to carry crown fire. As noted in previous surveys and studies, MPB-caused stand mortality in PICO stands is typically lower than 100% (Westfall and Ebata 2011, Simard *et al.* 2012). Very high mortality levels (greater than ~75%) within a stand can also take several years to develop during the course of an epidemic (Cole and Amman 1980). A recent study used the complex physics-based Wildland-Urban Interface Fire Dynamics Simulator model to examine the effects

of stand structure and MPB attack proportion (red stage) on simulated fire behaviour (Hoffman *et al.* 2012). The results suggested that MPB attack had a highly significant effect on crown fire involvement, but that the spatial arrangement and structure of simulated stands were also influential. Additional studies using mechanistic fire behaviour models may ultimately provide a more complete explanation. At the present, we speculate that the heightened spread rates observed in the present study occurred due to a combination of increased foliar flammability, increased availability of desiccated fine branch fuels in crowns, incomplete or delayed loss of foliage in older post-attack stands, and increased wind speed and solar radiation within affected stands.

It is also notable that the fuel types with the most intense and rapidly spreading fire behaviour potential in the FBP System are the M-3 and M-4 spruce budworm (*Choristoneura fumiferana*)-killed balsam fir types (FCFDG 1992, Wotton *et al.* 2009). Although the MPB-killed pine stands in this study and M-3 and M-4 stands represent insect-killed conifer stands, balsam fir is a much more shade-tolerant species that grows in moist, uneven-aged stands with very low crown base heights. Repeated defoliation of balsam fir tends to create very dense and multi-storied, lichen-covered fuelbeds with continuous fine dead branch fuels from the forest floor to the canopy (Stocks 1987). MPB-affected lodgepole pine forests are relatively taller and retain a single-storied structure with a distinct fuel strata gap, reducing their crowning potential somewhat compared to the M-3 and M-4 stands. Some of the fire observations in the present study did approach and even exceeded the speed of the predictions of the M-3 (100% dead balsam fir, leafless condition) fuel model, although in general the fire observations appeared bounded between the C-3 and M-3 (100% dead fir) model predictions (Figure 3).

Predicting Spread Rate in Beetle-Killed Pine Stands

This study presents several new equations for predicting ROS in pure lodgepole pine or pine-dominated stands that have been recently (1 to ~5 years) attacked by MPB and still contain some dead needles in their crowns. The data were mainly observations of crown fires at intermediate fire danger conditions, with few observations at the lower and higher ends of the scale. A few observations were identified as particularly influential in the models according to their Cook's *D* values, particularly one observation at much higher fire danger conditions. This highlights the need for additional observations, particularly at ISI values ~12 or greater; however, there is no reason for doubting the accuracy of observation 2 otherwise. Although the models are presented to provide an estimate of ROS at low to moderately high ISI levels (<25), over 40% of the variability in observed ROS remains unexplained, and they will not necessarily result in accurate predictions. It is likely that variations in fuel structure (e.g., variations in MPB impact and timing, canopy heights between 16 m to 22 m based on inventory estimates, canopy base heights unknown for most fires) and measurement error (wind speed and direction, fire position on photographs) account for a significant proportion of the residual error. The influence of atmospheric instability on the column development and spread of these fires was also not considered, despite being recognized as a very important factor in large fire growth (Schroeder and Buck 1970, Nelson 2003). However, even experimental studies with much more homogeneous fuel complexes and precise measurements of fuels and weather conditions have encountered considerable variation in observed and predicted spread (e.g., Stocks *et al.* 2004). This may be due to other, seldom-studied phenomena, such as variability in fuel arrangement within sites (e.g., Hoffman *et al.* 2012).

Fire spread is a complex process that was treated very simply in this study. Our approach was initially similar to that used in the FBP System for most of the existing FBP fuel types in which, for convenience, a single equation predicts all types of fire behaviour (surface fire, intermittent crowning, active crown fire, and the contribution of spotting); the point of inflection on the sigmoidal curve (Equation 2) represents where transition to crowning occurs (FCFDG 1992). However, the shape of the curve is constrained by the number of parameters, and it is not possible to obtain a sharp transition between surface and crown fire with the 3-parameter curve form. Furthermore, forcing the ROS through the origin may overestimate surface fire spread rates at low wind speeds.

More recent studies have suggested that the transition from surface to crown is often more abrupt (Cruz *et al.* 2005, Alexander and Cruz 2011). This concept was used in our Model 4 (Table 3, Figure 3), developed as a dual equilibrium curve with an instantaneous transition point associated with a critical surface fire intensity to induce crowning. The data only partly support this pattern, as there is overlap between the ISI levels associated with surface fires and crown fires. The crown fire transition point of ISI 5.5 seems low, and further testing will be required to improve this estimate. Visual inspection of the data suggests that a plausible crown fire threshold ISI may be anywhere from ~5 to 7. Among individual observations, crown fire behaviour (intermittent or active) was observed in all fire runs with ISI greater than 6.5⁴.

In the FBP System, the gradual (rather than instantaneous) transition to crown fire is based on the Crown Fraction Burned (CFB) function (FCFDG 1992, but see Cruz and Alexander 2010). Thus, a comparable crowning thresh-

old using the C-3 fuel type would probably be defined as either ISI 11.6 (for the lower limit of intermittent crown fire, defined as $0.1 \leq \text{CFB} \leq 0.9$) or ISI 13.3 (for $\text{CFB} = 0.5$); both values assume no Buildup Index (BUI) effect on ROS. The lower limit of active crown fire (defined as $0.9 \leq \text{CFB} \leq 1.0$) in the C-3 fuel type is found at ISI 17.2, assuming no BUI effect (calculated from FCFDG 1992).⁵

The analysis of two wildfires in unattacked conifer stands, using similar photo-interpretation methods as were used on the MPB data, showed a very close relationship between observed and predicted ROS. Although this does not prove that the methods are accurate, it does suggest that wildfire photographs can be analyzed to produce credible spread rates using the FBP System when a fuel type match is easily identified. Additional exploration of the PATC photo database and of photo-interpretation methods is currently ongoing and may yield additional fire behaviour findings in various fuel complexes.

Aside from spread rate, the fire behaviour measure of greatest interest is probably fireline intensity. In several fire modeling systems, including the FBP System, headfire intensity (HFI) is calculated from Byram's (1959) equation, $I = HwR$, where I is fireline intensity, H is the constant heat of combustion of forest biomass, w is the weight (mass) of consumed fuel (typically measured in experimental burns), and R is ROS. Thus, HFI increases proportionally with ROS if fuel consumption is undiminished. The only data we have found on fuel consumption in recent MPB-affected stands was unpublished work done by Hawkes and others (B. Hawkes, Natural Resources Canada, Pacific Forestry Centre, personal communication), who studied the effects of an intense wildfire in MPB-affected climax lodgepole pine stands on the Chilcotin Plateau

⁴ An ISI value of 5.5 is equivalent to a 10 m wind speed of approximately 2.7 km h⁻¹ at 10% fine fuel moisture content; ISI of 6.5 is equivalent to 10 m winds of 6.0 km h⁻¹ at 10% fine fuel moisture.

⁵ See footnote 4; at 10% fine fuel moisture content, ISI values of 11.6, 13.3, and 17.2 are equivalent to wind speeds of approximately 17.5 km h⁻¹, 20.2 km h⁻¹, and 25.3 km h⁻¹, respectively.

(close to the location of fire 3 in this study). That study reported total fuel consumption of 6.27 kg m^{-2} , or 13% greater than predicted using the C-3 model. Although more research on this topic is needed, it is very likely that HFI is heightened during the first 5 years following MPB attack due to increased ROS (this study), and increased or at least undiminished fuel consumption.

Uncertainty in Post-Beetle Fuel Succession

Characterizing the fuel structure of an MPB-affected pine stand is not trivial: as previous authors have noted, beetle attacks in lodgepole pine stands occur unevenly in time and space, often resulting in a mix of red, green, and gray stems simultaneously in a stand for several years and forming a highly heterogeneous fuel structure (Cole and Amman 1980, Wulder *et al.* 2006, Jenkins *et al.* 2012). The overstory composition in some of the stands in the present study included secondary (shade-tolerant) conifer species as well as healthy green pines. The understory composition, which was not measured on most fires, likely included varying densities of smaller conifer saplings (depending on stand history and productivity), which can act as ladder fuels and greatly influence crown fire initiation (Cruz *et al.* 2003, Agee and Skinner 2005). Because the MPB outbreak mapping was accomplished by visual observers in airplanes, it was not always possible to identify the exact year of attack; for example, Westfall and Ebata (2009: 15) describe how difficulties with “unusually high needle retention” in 2007 attacks made identifying new attack areas in 2008 and 2009 more difficult. To the extent that fuel structure can be meaningfully described at the stand level, the findings from this study should apply most directly to red-attack and early grey-attack lodgepole pine stands, with secondary tree species and understory compositions similar to the dry lodgepole pine forests of north-central interior British Columbia.

Some previous reports have suggested that MPB-killed stands may pose a fuels hazard many years after beetle attacks. Understory releases of various conifer species have been documented to occur 2 to 10 years after MPB outbreaks (Cole and Amman 1980, Heath and Alfaro 1990) and could contribute to increased fuel loading and fuel continuity in the post-MPB regenerating stand (Jenkins *et al.* 2008). A recent experimental burn was conducted in heavy fuels ~20 to 25 years after severe MPB attacks in an eastern British Columbia lodgepole pine stand; measured spread rates were comparable to those in this study: ROS of 27.6 m min^{-1} at an adjusted ISI of 9.4 (Kubian *et al.* 2009). Similarly, explosive crown fire behaviour was described many years earlier on the 1961 Sleeping Child Fire (Montana, USA), 30 to 35 years post-MPB attack, as discussed recently by Jenkins *et al.* (2012). Some of the areas most heavily affected by MPB may gradually resemble heavy slash as the dead overstory trees collapse; however, very little data on fire behaviour in these stands is currently available and most assumptions are still based on model outputs.

The dynamically evolving fuel complexes resulting from post-MPB stands will be a dominant feature across affected areas in western North America for many years in the future as the recent outbreak ages. These few anecdotes suggest that MPB-attacked stands in the older post-epidemic (grey) stages of attack may once again support extreme fire behaviour, although differences in post-disturbance successional pathways could result in widely varying fuel structure outcomes in regenerating stands.

Conclusions

Although some previous simulation studies suggest otherwise, the observations in this study provide evidence for more rapid crown fire behaviour and very rapid spread in the first few years following MPB attack under moderate fire danger conditions. This study also produced prediction models for ROS following

the Canadian FBP System approach by using a combination of experimental burns and wildfire observations. Models 1 and 4 from this study can be used with caution for predicting spread rate in recent MPB-attacked mature pine stands. Due to the limited extent of the data, the models presented in this study should not be used for prediction above moderate to high ISI levels (~25 to 30), and may underpredict fire spread during extreme fire danger conditions.

Fire management agencies in western North America are confronted annually with wildfires in beetle-killed conifer fuels and must use various imperfect techniques to predict fire behaviour for the purposes of safety, operational efficiency, and forest management decision-making. The commonly used tools for fire behaviour forecasting, including the existing FBP System and derived guides and software (e.g., Taylor *et al.* 1997, Tymstra *et al.* 2010) as well as applications designed for use with the Rothermel (1972)-based modeling systems (e.g., Finney 2004, Andrews *et al.* 2008) do not cover MPB-killed stands adequately to date. While custom fuel models can be assembled (e.g., Simard *et al.* 2011), they have not yet been validated with field observations and may significantly underestimate ROS or fire intensity. Although the models we developed in this study are based on a limited number and range of observations, their use may reduce the uncertainty associated with fire behaviour prediction in MPB-killed pine stands.

For most Canadian fire management agencies, the CFFDRS/FBP System is the basis for training and decision support; thus, models that are readily understood and integrated with this framework are much more valuable and usable. The four models from this study are currently being tested operationally by fire crews in western Canada for use in early post-attack stands. However, due to the lim-

ited area of new MPB outbreaks (red-attack stands) currently in British Columbia, these models may have more utility in other geographic areas that are currently in MPB epidemic conditions. For field and operational calculations, we have also noted that the M-3 FBP fuel type with approximately 65% dead balsam fir yields quite similar ROS predictions to those of Model 2 (for ISI less than 25) and can therefore be readily approximated using currently available software and tools.

An additional finding from this study is that oblique photographs of fire behaviour taken from the air could be effectively used for estimating spread rates. Other photographic records are currently being examined for their potential in fire behaviour analyses, and much work could be done to improve the interpretation process. For managers also contemplating the use of such photographs for research purposes, we have noted that near-nadir views produce the greatest positional accuracy, but side profiles of the flaming front (flames visible underneath the smoke column) are superior for identifying fire type and fire behaviour details. Photos should be from a wide angle perspective so that landscape features are visible as much as possible. Higher resolution will permit zooming in to identify landscape features, vegetation, and fire behaviour details. Finally, ensuring proper time settings on digital cameras will help reduce confusion in spread rate calculations.

Fuel conditions and fire hazard of large areas of MPB-killed lodgepole pine forest in western North America will continue to evolve for many years after beetle attack. The British Columbia experience during the past decade has been one of heightened fire behaviour during epidemic MPB conditions in pine stands. Further refining these models, and quantifying future fire behaviour under various successional pathways, remain topics for further study.

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