Modeling *Pinus strobus* mortality following prescribed fire in Quetico Provincial Park, northwestern Ontario

Jennifer L. Beverly and David L. Martell

Abstract: In forest ecosystems where ecologically beneficial fire impacts are promoted through the use of prescribed fire, predictive models of fire effects, such as tree mortality, are essential for assessing the ecological consequences of fire management options. Impact of tree size, fire intensity, and fuel characteristics on postfire eastern white pine (*Pinus strobus* L.) mortality was evaluated 10 months following a prescribed fire in Quetico Provincial Park, northwestern Ontario. A logistic regression model was developed to predict white pine mortality following an intense surface fire (1200 kW/m). Overall fire-caused mortality was relatively low (17.0%). Probability of mortality increased with increasing height of stem blackening, a surrogate measure of fire intensity, and decreased with increasing tree diameter at 1.3 m (DBH). White pine with ≥20 cm DBH were found to be highly resistant to intense surface fire. The model can be used to predict postfire mortality in white pine stands with a mixedwood understory in the Great Lakes – St. Lawrence forest region of Ontario.

Résumé : Les modèles de prédiction des effets du feu, tels que la mortalité des arbres, sont essentiels pour évaluer les conséquences écologiques de diverses options de gestion du feu dans les écosystèmes forestiers où les impacts du feu qui sont bénéfiques d’un point vue écologique sont favorisés via l’utilisation du brûlage dirigé. L’impact de la dimension des arbres, de l’intensité du feu et des caractéristiques des combustibles sur la mortalité après feu du pin blanc (*Pinus strobus* L.) a été évalué 10 mois après un brûlage dirigé dans le parc provincial de Quetico situé dans le Nord-Ouest de l’Ontario. Un modèle de régression logistique a été développé pour prédire la mortalité du pin blanc à l’ suite d’un feu de surface de forte intensité (1200 kW/m). Dans l’ensemble, la mortalité due au feu était relativement faible (17.0 %). Les risques de mortalité augmentent avec la hauteur du noircissement de la tige, une mesure qui remplace l’intensité du feu, et diminuent en fonction du diamètre à 1,3 m (DHP). Le pin blanc avec un DHP ≥20 cm est très résistant à un feu de surface de forte intensité. Le modèle peut servir à prédire la mortalité après feu dans les peuplements de pin blanc avec un sous-étage composé d’essences mixtes dans la région du Saint-Laurent et des Grands Lacs, en Ontario.

Introduction

Eastern white pine (*Pinus strobus* L.) is a commercially important tree species in eastern North America (Chapeskie et al. 1989) that is valued highly for wildlife habitat (Naylor 1994), aesthetic qualities (Haider 1994), and as a provincial symbol in Ontario (Farrar 1995). Decline in white pine abundance throughout the Great Lakes – St. Lawrence forest region of Ontario has been attributed to intensive historical harvesting activities followed by unsuccessful regeneration (Bowling and Niznowski 1996; Carleton et al. 1996). Although incidence of white pine self-replacement has been documented in Ontario (Quinby 1991), widespread regeneration failure has been associated with poor seedbed quality and competitive vegetation that occurs on mineral soils where white pine typically grow (McRae et al. 1994).

White pine seedling emergence increases with the removal of both soil organic matter (Herr et al. 1999) and competitive vegetation (Burgess and Wetzel 2000), conditions that are typically associated with surface fires (Methven and Murray 1974; Van Wagner and Methven 1978). Noncatastrophic surface fires are characteristic of white pine forests (Maissurow 1935, 1941; McRae 1994), recurring historically every 10–80 years in these ecosystems (Swain 1973; Heinselman 1973; Woods and Day 1977; Burgess and Methven 1977; Dey and Guyette 1996a, 1996b). Prescribed surface fire has been shown to facilitate white pine seedling establishment (Blankenship and Arthur 1999), and it has been suggested that fire suppression programs have had a negative impact on white pine regeneration by reducing the prevalence of sites where competitive vegetation and soil organic matter have been removed by fire (Burgess et al. 1999). According to McRae et al. (1994), the survival of remaining white pine stands in Canada may depend on the re-introduction of fire into these ecosystems.

Managers need the ability to predict postfire white pine mortality to use prescribed fire effectively in these stands be-
cause extensive mortality caused by crown fires or high-intensity surface fires can lead to replacement by trembling aspen (Populus tremuloides Michx.) (Frelich and Reich 1999) by destroying the live seed source necessary for postfire white pine regeneration (Van Wagner et al. 1978). Prescribed fire planning in white pine ecosystems has been constrained by the few existing studies of white pine fire resistance, which are limited to descriptive statistics of postfire white pine mortality following, for example, prescribed fire in Kentucky (Blankenship and Arthur 1999) and experimental fires in the Great Lakes–St. Lawrence forest region of Ontario (Methven 1971). Statistical models are necessary for predicting postfire tree mortality and have been developed for numerous other tree species and forest types using logistic regression methods (Table 1).

Applications of postfire tree mortality models were reviewed previously and prescribed fire planning was consistently identified as a management activity that could be enhanced by the use of such models (Van Wagner 1973; Waldrop and Van Lear 1984; Wyant et al. 1986; Brown and DeByle 1987; Regelbrugge and Smith 1994; Blankenship and Arthur 1999). Because tree mortality is an important ecological process that alters population and community structures (Volney 1998; Reinhardt et al. 2001), releases nutrients, increases duration and intensity of light penetration through the canopy, and creates new habitat (Franklin et al. 1987), postfire tree mortality models are also important for enhancing our understanding of ecological responses to forest fires (Van Wagner 1973; Reinhardt et al. 2001). Other potential applications have been identified as quantification of economic fire losses (Van Wagner 1973; Peterson and Arbaugh 1989), salvage cutting (Dixon et al. 1984; Wyant et al. 1986; Peterson and Arbaugh 1989; Linder et al. 1998), and modeling changes in resource outputs, such as timber production or vegetation (Peterson and Arbaugh 1989; Reinhardt et al. 2001).

Models of postfire tree mortality typically predict mortality as a function of tree attributes, observable fire damage, and fire behaviour characteristics. Tree attributes such as bark thickness (Harmon 1984; Ryan and Reinhardt 1988; Peterson and Arbaugh 1989) or diameter at 1.3 m (DBH) (Bevins 1980; Wyant et al. 1986; Brown and DeByle 1987; Saveland and Neuenschwander 1990; Regelbrugge and Smith 1994; Mutch and Parsons 1998; Linder et al. 1998; Guinto et al. 1999) are used to represent the physical characteristics of trees that influence their susceptibility to forest fire damage. Bark thickness insulates the cambium from lethal temperatures and is correlated with DBH (Hengst and Dawson 1994). For species where the distance between the crown base and the understory increases with height, DBH, as an easily measured correlate of height, can indicate crown susceptibility to scorching (Van Wagner 1965) and resultant foliage death due to the release of convective hot gases (Van Wagner 1973).

Van Wagner (1970) reported that crown scorch rather than cambium damage was the principal cause of postfire pine mortality, and extent of crown scorch has been used extensively to predict tree mortality (Peterson and Arbaugh 1989; Ryan and Reinhardt 1988; Finney and Martin 1993; Mutch and Parsons 1998; Menges and Deyrup 2001). Measures of bole damage (Peterson and Arbaugh 1989; Brown and DeByle 1987) are used less often. The physiological processes that lead to tree mortality as a result of crown scorch are poorly understood. For white pine, inhibition of bud development and subsequent mortality ensues possibly due to needle loss or as a direct result of exposure to high temperatures (Methven 1971). The timing of the fire may also affect postfire mortality; for example, McRae et al. (1994) suggested that white pine may survive severe crown scorch if the fire occurs prior to bud emergence.

Few studies relate postfire tree mortality to direct observations of fire behaviour parameters such as intensity (Weber et al. 1987) or flame length (Finney and Martin 1993). Fire intensity refers to the heat energy released from a fire. Frontal fire intensity is defined as the rate of heat energy release per unit time per unit length of fire front (Byram 1959) and is directly related to flame length and height (Alexander 1998). As fire intensity increases, there is increasing potential for consumption of crown fuels (Van Wagner 1977) from flare-ups or torching of individual trees and crown damage from scorching (Van Wagner 1973). Variation in surface fire behaviour across a stand in response to microlevel changes in fuel, weather, and topography necessitates the use of tree-specific physical evidence to infer fire intensities associated with individual trees. Surrogate, tree-specific measures of fire intensity include the maximum height of fire-killed foliage in the crown above the burn (crown scorch height) (Bevins 1980; Saveland and Neuenschwander 1990; Swezy

### Table 1. Logistic regression models of postfire tree mortality.

<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Species</th>
<th>Independent variable(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bevins 1980</td>
<td>Montana</td>
<td>Douglas-fir</td>
<td>DBH, scorch height</td>
</tr>
<tr>
<td>Brown and DeByle 1987</td>
<td>Wyoming, Idaho</td>
<td>Aspen</td>
<td>DBH, char height, circumference charred</td>
</tr>
<tr>
<td>Ryan and Reinhardt 1988</td>
<td>Northwest U.S.A.</td>
<td>Conifers</td>
<td>Crown killed, bark thickness</td>
</tr>
<tr>
<td>Peterson and Arbaugh 1989</td>
<td>Cascade Range</td>
<td>Douglas-fir</td>
<td>Crown scorch, basal scorch, depth of bark char, cambial condition</td>
</tr>
<tr>
<td>Saveland and Neuenschwander 1990</td>
<td>Idaho</td>
<td>Ponderosa pine</td>
<td>Scorch height, DBH</td>
</tr>
<tr>
<td>Finney and Martin 1993</td>
<td>California</td>
<td>Coastal redwoods</td>
<td>DBH, flame length, surface fuel consumption, crown scorch</td>
</tr>
<tr>
<td>Regelbrugge and Smith 1994</td>
<td>California</td>
<td>Mixed oak forest</td>
<td>DBH, height of stem bark char</td>
</tr>
<tr>
<td>Mutch and Parson 1998</td>
<td>California</td>
<td>Conifer</td>
<td>Crown volume scorch, DBH</td>
</tr>
<tr>
<td>Linder et al. 1998</td>
<td>Northern Sweden</td>
<td>Scots pine, Norway spruce</td>
<td>DBH</td>
</tr>
<tr>
<td>Guinto et al. 1999</td>
<td>Australia</td>
<td>Eucalypt forests</td>
<td>DBH</td>
</tr>
</tbody>
</table>

**Note:** DBH, tree diameter at 1.3 m.
and Agee 1991; Mutch and Parsons 1998) or the height of stem char (Weber et al. 1987; Brown and DeByle 1987; Regelbrugge and Smith 1994; Menges and Deyrup 2001).

Van Wagner (1973) developed an empirical model relating the height of crown scorch to fire intensity, and postfire observations of scorch height have been used to model tree mortality (Bevins 1980; Saveland and Neuenschwander 1990; Swezy and Agee 1991; Mutch and Parsons 1998). Measures associated with tree stems, such as char height, are considered preferable to crown scorch measures due to their permanence (Dixon et al. 1984) and ease of collection (Cain 1984). Weber et al. (1987) reported a strong correlation between mean char height and percent tree mortality in eastern Ontario jack pine (Pinus banksiana Lamb.) stands following experimental fires. Char height was also identified as a significant determinant of postfire tree mortality for south Florida slash pine (Pinus elliotti var. densa) (Menges and Deyrup 2001), mixed oak forests in Virginia (Regelbrugge and Smith 1994), and aspen (Brown and DeByle 1987).

Fuel load, or dry fuel mass per unit area, is a key determinant of fire intensity (Whelan 1995). Efforts to include fuel characteristics in postfire tree mortality models include the use of independent variables such as depth of ground char (Swezy and Agee 1991), surface fuel consumption (Finney and Martin 1993), the season of burn (Swezy and Agee 1991), and the presence of coarse woody debris (McCaw et al. 1997). Investigating the relationship between fuel characteristics and tree mortality is particularly pertinent to prescribed fire planning, since prescribed fires are often used to reduce fire hazard associated with excessive fuel accumulations.

The objective of this study was to develop a logistic regression model for predicting white pine mortality following a prescribed surface fire in Quetico Provincial Park as a function of tree, fire, and fuel characteristics. The prescribed fire was ignited to reduce fire hazard in an area of heavy blowdown damage, but it also spread naturally into healthy, undamaged white pine stands adjacent to the continuous blowdown areas. Given the likelihood of additional prescribed fires in the area and the need for prefire risk assessments of potential white pine mortality in healthy stands adjacent to the blowdown, we used independent variables that are readily available to managers prior to the ignition of a fire to develop a predictive statistical model for assessing potential fire effects in healthy white pine stands. From these results, we consider the implications of fire-induced white pine mortality for fire, park, and forest management planning.

Study site

Description

The study was conducted on a gentle, south-facing slope along the northern shore of Knife Lake (48°05’N, 91°15’W, elevation 450 m), which is part of the southeast international boundary that separates Quetico Provincial Park in Ontario from the Boundary Waters Canoe Area (BWCA) wilderness of northern Minnesota. Quetico Provincial Park is located in a transitional zone between the southern deciduous forest of eastern North America and the northern coniferous boreal forest (Hills 1959) and is characterized by glacial clay deposits, glacial sand deposits, and irregular terrain (Rowe 1972). Situated within the boreal shield ecoregion in the southern portion of Hills’ (1959) Pigeon River site region (4W1), the area is covered by predominantly boreal vegetation, such as jack pine, black spruce (Picea mariana (Mill.) BSP), trembling aspen, and white birch (Betula papyrifera Marsh.) (Walshe 1980). Reduced in extent by historical logging activities, white pine currently occurs in approximately 18% of the 4758-km² park area and is a dominant species (<50% composition) in less than 5% of that area (Bowling and Nizowski 1996). Despite their relative lack of abundance in the park, these protected white pine ecosystems represent a significant portion of white pine stands that remain in northeastern Ontario (Perera and Baldwin 1993).

Prior to the prescribed fire, the 12-ha study site contained a mature white pine overstory with a basal area of 5.7 m²/ha and a dominant height of 20.6 m. Characterized by scattered red pine (Pinus resinosa Ait.) and a mixedwood understory, the site corresponds to the C-5 (red pine and white pine) and M-I/M-2 (boreal mixedwood) fuel types of the Canadian Forest Fire Behavior Prediction (FFB) System (Forestry Canada Fire Danger Group 1992). In northwestern Ontario, white pine mixedwood forests are characterized by an overstory of white pine and an understory of other tree species such as white birch, trembling aspen, balsam fir (Abies balsamea (L.) Mill.), white spruce, eastern white-cedar (Thuja occidentalis L.), black spruce, jack pine, and red maple (Acer rubrum L.) (Sims et al. 1989). Dense understory shrub layers are dominated by beaked hazel (Corylus cornuta Marsh.) and balsam fir (Sims et al. 1989). Craig (1972) conducted a 10 000-year vegetation history of the area from pollen analysis of sediment taken from Lake of the Clouds, which is approximately 7 km northeast of the study site. These pollen records identify the introduction of white pine into spruce and jack pine dominated forests about 7000 years ago, followed by a period of white pine dominance (6500–3000 years before present) and eventual decline (<3000 years before present) at the expense of increased spruce and cedar.

Fire history

Prior to the prescribed fire, there were no fires reported in the area for the 80-year period for which continuous historical fire records are available (Ontario Ministry of Natural Resources 2001; Woods and Day 1977; Donnelly and Harrington 1978). Heinselman (1996) reported that forests directly south of the study area were logged extensively in the early 1900s and this area experienced large fires in 1910, which spread into uncut forests east of Knife Lake; however, there are no confirmed logging or fire records available to substantiate stand origin of our study site on the northern shore of Knife Lake.

Swain (1973) conducted a 1000-year fire history based on sediment charcoal records from Lake of the Clouds, 7 km northeast of the study site. Average fire frequency was determined to be 60–70 years with a range of 20–100 years. While fire-free periods longer than 100 years have occurred at Lake of the Clouds, Swain (1973) considered this an unlikely interval for the region as a whole and predicted decreased levels of pine under continued fire suppression. These results are consistent with the 78-year natural fire frequency estimated by Woods and Day (1977) for Quetico
Provincial Park and the 100-year natural fire frequency estimated by Heinselman (1973) for the BWCA. In comparison with the 1830–1930 period, recent fire activity in Quetico has decreased dramatically (Woods and Day 1977). In 1936, three large fires consumed 41,650 ha in the central and northwest areas of the park (Woods and Day 1977), and in 1995, a single fire consumed 25,085 ha (Lynham and Curran 1998). Large fires in the park were also reported in 1961 (4600 ha), 1972 (2330 ha), and 1996 (1780 ha). The recognition of fire as an important ecological process in Quetico resulted in the implementation of a fire management plan in 1998 to promote the ecological benefits of wildfire, and the first Prescribed Natural Fire (PNF) occurred in June 1999 (Peruniak 2000).

Prescribed fire conditions

In July 1999, a severe windstorm resulted in over 291,000 ha of blowdown damage in the region, with the majority of the damage in the BWCA and 11,000 ha affected in the southeast corner of Quetico Provincial Park. Extreme wind damage north of Knife Lake occurred in a relatively continuous belt that traversed the international border and created potential for a cross-border fire originating in the United States. On October 12, 2000, the Ontario Ministry of Natural Resources conducted a prescribed fire to create a fuel break between Quetico and the blowdown area in the BWCA wilderness (Fig. 1) and to reduce general wildfire hazard in the area. No effort was made to suppress the blowdown fire, and once ignited, it was simply monitored until it reached natural barriers, such as lakes, or fuel conditions that could not support combustion. In several areas, the fire spread naturally from the belt of continuous blowdown into healthy red and white pine stands adjacent to the blowdown. It was hoped that the prescribed fire would provide beneficial ecological effects by promoting regeneration in these healthy red and white pine stands, which were undamaged in the windstorm but were subjected to a naturally spreading understory fire (Ontario Ministry of Natural Resources 2000).

Table 2. Fire weather and fire weather index components at Kashapiwi (observations at 13:00 for ignition date October 12, 2000).

<table>
<thead>
<tr>
<th>Fire weather</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>18.5</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>43</td>
</tr>
<tr>
<td>Wind direction (degrees)</td>
<td>191</td>
</tr>
<tr>
<td>Wind speed (km/h)</td>
<td>5</td>
</tr>
<tr>
<td>Precipitation</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Canadian forest fire weather index componentsa</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFMC 89.9 H</td>
</tr>
<tr>
<td>DMC 13 L</td>
</tr>
<tr>
<td>DC 238 M</td>
</tr>
<tr>
<td>ISI 5.4 H</td>
</tr>
<tr>
<td>BUI 23 M</td>
</tr>
<tr>
<td>FWI 9.2 M</td>
</tr>
</tbody>
</table>

| Note: FFMC, fine fuel moisture code; DMC, duff moisture code; DC, drought code; ISI, initial spread index; BUI, buildup index; FWI, fire weather index. |

The Emerald Lake prescribed fire occurred under moderate fire weather conditions as defined by the Canadian Fire Weather Index system. The fire weather and fire weather index components recorded on the day of ignition at the Kashapiwi weather station located 15 km north of the study area are summarized in Table 2. Under these weather conditions, the FBP (Forestry Canada Fire Danger Group 1992) predicts a low-intensity (10–500 kW/m) surface fire in the red and white pine fuel types (C-5) with equilibrium rates of spread of 0.2 m/min and of 0.2- to 1.4-m flame lengths. In leafless boreal mixedwood fuel types (M-1) with a 50% conifer component, the FBP predicts a low-vigour to highly vigorous surface fire (500–2000 kW/m) with equilibrium rates of spread of 2 m/min and 1.4- to 2.6-m flame lengths.

Two centre fires were ignited by a specialized drip-torch slung and activated from a helicopter (helitorch) at 11:45
a.m. in an elevated area of heavy blowdown north of the study site. Convection associated with the centre fires helped to control rates of fire spread as strip-ignition patterns were used to support a head fire spreading southwest through the blowdown. The fire eventually spread from the blowdown and backed down-slope through the study site of healthy, undamaged standing white pine without the aid of manual ignition in this area. Half-hourly observed weather and associated fire behaviour predictions for the period during which the study site was burned were recorded at the Prairie Portage weather station located 15 km southwest of the study area (Table 3). Observed rates of spread in the C-5 and M-1 study area were 1–2 m/min with flame lengths of approximately 1–3 m, indicating a fire intensity of approximately 1200 kW/m. Correspondence between predicted and observed fire behaviour suggests that the weather measurements recorded off-site were representative of conditions in the study area. Final fire size reached 1620 ha, with negligible fire spread beyond the day of ignition. On-site precipitation of 16.5 mm between 25 and 49 h postignition resulted in minimal sustained smouldering.

Table 3. Half hourly fire weather and fire weather danger ratings at Prairie Portage for the ignition date October 12, 2000.

<table>
<thead>
<tr>
<th>Time</th>
<th>Temperature (°C)</th>
<th>Relative humidity (%)</th>
<th>Wind direction (°)</th>
<th>Wind speed (km/h)</th>
<th>FFMCa</th>
<th>ISIb</th>
<th>M-1</th>
<th>C-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>13:00</td>
<td>17.9</td>
<td>41</td>
<td>360</td>
<td>1.6</td>
<td>88.6 H</td>
<td>3.8 M</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>13:30</td>
<td>18.6</td>
<td>40</td>
<td>360</td>
<td>3.2</td>
<td>88.9 H</td>
<td>4.3 M</td>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td>14:00</td>
<td>19.8</td>
<td>38</td>
<td>360</td>
<td>1.6</td>
<td>89.3 H</td>
<td>4.2 M</td>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td>14:30</td>
<td>19.9</td>
<td>39</td>
<td>360</td>
<td>1.6</td>
<td>89.4 H</td>
<td>4.3 M</td>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td>15:00</td>
<td>20.6</td>
<td>38</td>
<td>360</td>
<td>1.6</td>
<td>89.6 H</td>
<td>4.4 M</td>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td>15:30</td>
<td>21.1</td>
<td>35</td>
<td>245</td>
<td>3.2</td>
<td>90.1 E</td>
<td>5.1 H</td>
<td>3</td>
<td>0.2</td>
</tr>
<tr>
<td>16:00</td>
<td>21.5</td>
<td>35</td>
<td>315</td>
<td>3.2</td>
<td>90.3 E</td>
<td>5.3 H</td>
<td>3</td>
<td>0.2</td>
</tr>
<tr>
<td>16:30</td>
<td>21.2</td>
<td>36</td>
<td>290</td>
<td>1.6</td>
<td>90.4 E</td>
<td>4.9 H</td>
<td>3</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Letters refer to Ontario fire weather index classes (FFMC, fine fuel moisture code; ISI, initial spread index) (Ontario Ministry of Natural Resources 2002): M, moderate; H, high; E, extreme.

Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992) fuel type: M-1, boreal mixedwood, leafless (50% conifer); C-5, red and white pine.

Materials and methods

Field measurements

Postfire white pine mortality was investigated in August 2001, 10 months after the prescribed fire. Sixteen parallel transects were laid out perpendicular to the edge of continuous blowdown areas in a north–south direction at intervals located at least 50 m apart and situated to maintain constant slope and aspect and uniform site conditions. Transects were limited to the north by the edge of continuous blowdown and to the south by the Knife Lake shoreline. Along each transect, sample points were located randomly with a minimum distance of 50 m between each point. The point-centred quarter method (Cottam and Curtis 1956; Krebs 1989) was used to identify four sample trees ≥1.3 m in height at each of 41 sample points. Four additional sample points had only three sample trees because the proximity of the lakeshore precluded the location of a white pine tree in one of the quadrants.

Data were recorded for 176 trees. Tree status was classified as either live or dead. Any tree devoid of green needles was classified as dead. Dead trees that lacked evidence of recent fire damage, such as the presence of red or brown needles either on or beneath the tree, were classified as dead prior to the burn and were excluded from the analysis. Standing trees that were severely damaged by the fire but still had some green foliage were classified as living. For live trees that were damaged by the fire, percent crown damage indicated by fire-induced loss or burning of foliage was determined by ocular estimation as <25, 25–49, 50–74, or ≥75%. Tree height and DBH were measured with clinometers and diameter tapes, respectively. Volume was calculated from DBH and height measurement using Honer’s (1967) white pine volume function (V):

\[ V = \frac{DBH^2}{0.691 + 363.676/H} \]

where DBH is the tree diameter at 1.3 m and H is tree height.

Because tree-specific measurements of prefire fuel loadings were unavailable for the study area, the fuel characteristics prior to the prescribed fire were inferred indirectly by evidence available in our postfire assessment. The status (present–absent) of coarse woody debris (>7 cm in diameter) located within 1 m of the stem was used in an effort to capture the degree of litter accumulation that may have resulted in the windstorm of July 1999. Transects through the study site were located perpendicular to the edge of a continuous belt of blowdown, and estimated fire intensity in fuel types that approximate blowdown exceeded estimates for the C-5 and M-1 fuel types found in our study area (Forestry Canada Fire Danger Group 1992). To account for the possibility of elevated fire intensity in the transition areas between the heavy blowdown and the healthy, undamaged standing white...
pine located in the study site, distance (m) from the edge of continuous blowdown was measured.

White pine bark has high thermal protection characteristics (Hengst and Dawson 1994), and cambium damage near the ground is usually a minor consideration in postfire mortality investigations for this species (Van Wagner 1973). However, because the prescribed fire backed down slope through the study site, there were elevated fire residence times in the standing white pine (T. Curran, personal communication), which increases the likelihood of bole damage (Gutsell and Johnson 1996) and subsequent tree mortality. Due to study site topography, we recorded the status (present–absent) of visible bole damage at the base of the tree to reflect the fire intensity implications associated with the sloping terrain. We use a simple visual assessment of the presence or absence of bole damage to avoid injury to the tree that can be caused by more accurate sampling methods that describe the extent of damage, such as the removal and analysis of cores for assessing cambial condition.

We used the maximum height of stem blackening (HSB) as a surrogate measure of fire intensity, and measurements were made with either a tape or clinometer, as required. The term “height of stem blackening” was chosen to differentiate between the numerous existing definitions of char height that appear in the literature, including the maximum height of charred surface (Finney and Martin 1993; Regelbrugge and Smith 1994; Pinard et al. 1999), the average between the upper and lower limit of char (Dixon et al. 1984), mean height of char (Brown and DeByle 1987; Weber et al. 1987), mean height of the blackened trunk (Menges and Deyrup 2001), and the vertical portion of the outer bark that was blackened by the fire (Cain 1984). Wyant et al. (1986) characterized asymmetric stem charring by calculating height of stem charring as a percentage of tree height in each of four bole quadrants, but this did not lead to increased discriminating power as compared with simpler char measures.

**Statistical analysis**

Predictions of postfire tree mortality commonly use a logistic model, which has the form

\[
P(m) = \frac{1}{1 + e^{-(b_0 + b_1x_1 + \ldots + b_n x_n)}}
\]

where \(P(m)\) is the probability of mortality in the interval 0 to 1, \(x_i\) through \(x_n\) are the independent variables, and \(b_0\) through \(b_n\) are the regression coefficients. The advantages of logistic regression models for postfire tree mortality assessments are reviewed in Regelbrugge and Smith (1994) and include predicted values between 0 and 1, parameter estimates and significance tests that do not require an assumption of normally distributed data, and predictions of binary or ordinal dependent variables from continuous, nominal, or ordinal independent variables.

We used logistic regression to model the probability of white pine mortality as a function of DBH, fire intensity, and fuel characteristics. HSB and the status (present–absent) of visible bole damage at the base of the tree were used as relative indicators of fire intensity. Fuel characteristics were represented by the distance from continuous blowdown (DFCB) and the status (present–absent) of coarse woody debris within 1 m of the stem. The probability of mortality was expected to correlate negatively with DBH and DFCB and positively with HSB, the presence of coarse woody debris within 1 m, and the presence of visible bole damage. These variables were tested for possible contributions to the model and the best model was selected on the basis of diagnostic statistics.

We assessed the potential for future mortality from the extent of crown damage to surviving trees. Methven (1971) found that mature white pine have a 50% chance of surviving the loss of three quarters of their foliage. A proportional odds model was developed to predict the probability that a surviving tree would experience crown damage <25, <50, and <75% as a function of the same variables included in the development of the postfire mortality model described above.

Maximum likelihood estimates of model parameters were computed with SAS LOGISTIC (SAS Institute Inc. 1995). Predictive ability and goodness of fit of the model were assessed by the likelihood ratio \(\chi^2\) test, the Wald \(\chi^2\) test for significance of individual parameters, and the \(C\) statistic (SAS Institute Inc. 1995). The \(C\) statistic measures the association between predicted probabilities and observed outcomes and is used to assess the performance of diagnostic systems. The \(C\) statistic is equivalent to the area under a receiver operating characteristic (ROC) curve and varies between 0 and 1, with improving performance approaching a value of 1. ROC curves have been used to evaluate logistic postfire tree mortality models (Regelbrugge and Smith 1994; Finney and Martin 1993), and the merits of this approach were reviewed by Saveland and Neuenschwander (1990).

**Results**

Postfire mortality was relatively low, representing 17.0% of white pine trees and 10.0% of prefire white pine volume. Percent mortality was greatest (29.0%) among white pine <10 cm DBH and correlated well with HSB classes (Fig. 2).
Mortality decreased with DFCB up to 149 m, increasing thereafter (Fig. 3). Postfire mortality resulted in a slight shift in the diameter distribution of living trees in the stand, with an increasing proportion in the larger DBH classes (≥20 cm) at the expense of smaller classes (Fig. 4).

The average DBH and DFCB were significantly greater for surviving trees as compared with fire-killed trees (Table 4). Average HSB was significantly greater for fire-killed trees than for surviving trees (Table 4). The proportion of stems with coarse woody debris within 1 m was not significantly different between live and fire-killed trees, and the proportion of trees with visible bole damage was not significantly different between live and fire-killed trees (Table 4).

Binary logistic regression was used to model the probability of postfire white pine mortality using DBH, HSB, DFCB, status of coarse woody debris, and status of visible bole damage as independent variables. Correlation analysis indicated no significant correlation between independent variables. The significance of individual parameters was determined by the Wald $\chi^2$ test. Coarse woody debris status (present–absent) and visible bole damage status (present–absent) were not significantly related to the probability of mortality and were removed from the model. Probability of mortality was correlated negatively with DFCB; however, due to the weak relationship ($p = 0.057$), this variable was also removed from the model. Contributions to the model by an interaction term between DBH and HSB proved insignificant. Probability of mortality as a function of DBH and HSB was predicted from the following model (Fig. 5):

#### Table 4. Diameter at breast height (1.3 m) (DBH), height of stem blackening (HSB), distance from continuous blowdown (DFCB) (A) and presence of coarse woody debris within 1 m of stem and presence of visible bole damage (B) for live and fire-killed white pine following prescribed fire in Quetico Provincial Park, northwestern Ontario.

<table>
<thead>
<tr>
<th></th>
<th>Live (n = 146)</th>
<th>Fire-killed (n = 30)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBH (cm)</td>
<td>29.2$^a$</td>
<td>22.7$^a$</td>
</tr>
<tr>
<td>HSB (m)</td>
<td>1.4$^b$</td>
<td>7.0$^b$</td>
</tr>
<tr>
<td>DFCB (m)</td>
<td>101.3$^c$</td>
<td>69.5$^c$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Live (n = 146)</th>
<th>Fire-killed (n = 30)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n Total</td>
<td>75</td>
<td>16</td>
</tr>
<tr>
<td>Coarse woody debris within 1 m of stem</td>
<td>0.5$^d$</td>
<td>0.5$^d$</td>
</tr>
<tr>
<td>Visible bole damage</td>
<td>8</td>
<td>0</td>
</tr>
</tbody>
</table>

$^a$Significant difference between live and dead trees (Wilcoxon rank sum test, $p = 0.056$).
$^b$Significant difference between live and dead trees (Wilcoxon rank sum test, $p < 0.001$).
$^c$Significant difference between live and dead trees (Wilcoxon rank sum test, $p = 0.004$).
$^d$No significant difference between live and dead trees ($\chi^2$, 1 df = 0.039, $p = 0.846$).
$^e$No significant difference between live and dead trees ($\chi^2$, 1 df = 1.722, $p = 0.189$).
Fig. 5. Predicted probability of postfire white pine mortality as a function of diameter at 1.3 m (DBH) and height of stem blackening (HSB) in Quetico Provincial Park, northwestern Ontario.

\[ P(m) = \frac{1}{1 + e^{-(0.8587 + 0.3595 \text{HSB} - 0.0766 \text{DBH})}} \]

where HSB is the height (m) of stem blackening and DBH is the tree diameter (cm) at 1.3 m. Standard errors of the coefficients in the order that they appear in the equation are 0.411, 0.076, and 0.022.

These results demonstrate that postfire white pine mortality is influenced by tree size and fire intensity. Predicted probabilities represent the probability that an individual white pine with a specific combination of DBH and HSB will be killed in the fire, or the proportion of all individuals with that same combination of DBH and HSB that will be killed. The probability of mortality was negatively correlated \((p = 0.001)\) with DBH and positively correlated with HSB \((p < 0.001)\). The likelihood ratio \(\chi^2\) statistic for goodness of fit indicated that the regression model was highly significant \((p < 0.001)\). The \(C\) statistic, which is equivalent to the area under the ROC curve, indicated 88.4% concordance between predicted probabilities and observed outcomes.

Crown damage to surviving white pine was relatively low, with 78.8% of surviving trees experiencing <25% crown damage (Table 5). Ordinal logistic regression was used to model the probability that a surviving tree would experience crown damage <25, <50, and <75% using DBH, HSB, DFCB, status of coarse woody debris, and status of visible bole damage as independent variables. The best proportional odds model for predicting the probability of crown damage levels for surviving trees included DBH and HSB as independent variables (Equation 6):

\[ \begin{align*}
\text{Pr}(<25\%) &= \frac{e^{0.3810 - 0.2864 \text{HSB} + 0.0556 \text{DBH}}}{1 + e^{0.3810 - 0.2864 \text{HSB} + 0.0556 \text{DBH}}} \\
\text{Pr}(<50\%) &= \frac{e^{1.7014 - 0.2864 \text{HSB} + 0.0556 \text{DBH}}}{1 + e^{1.7014 - 0.2864 \text{HSB} + 0.0556 \text{DBH}}} \\
\text{Pr}(<75\%) &= \frac{e^{2.4827 - 0.2864 \text{HSB} + 0.0556 \text{DBH}}}{1 + e^{2.4827 - 0.2864 \text{HSB} + 0.0556 \text{DBH}}}
\end{align*} \]

where \(P(<25\%)\) is the probability of <25% crown damage, \(P(<50\%)\) is the probability of <50% crown damage, \(P(<75\%)\) is the probability of <75% crown damage, HSB is height (m) of stem blackening, and DBH is tree diameter (cm) at 1.3 m. The standard errors of the coefficients in the order that they appear are 0.400, 0.077, and 0.017 (eq. 4), 0.464, 0.077, and 0.017 (eq. 5), and 0.559, 0.077, and 0.017 (eq. 6).

The probability of crown damage <25, <50, and <75% was positively correlated \((p = 0.001)\) with DBH and negatively correlated with HSB \((p < 0.001)\). The likelihood ratio \(\chi^2\) statistic for goodness of fit indicated that the proportional odds model was highly significant \((p < 0.001)\), with 79.1% concordance between predicted probabilities and observed outcomes as indicated by the \(C\) statistic.

### Discussion

White pine ≥20 cm DBH were found to be very resistant to vigorous surface fire (1200 kW/m), with 12.6% mortality or an input of standing dead trees into the ecosystem equivalent to 9.7% of prefire live white pine volume. Trees <20 cm DBH were less resistant, with 27.4% mortality. Surviving white pine had relatively little crown damage, with 78.8% of surviving trees experiencing <25% damage. Only 4.1% of surviving white pine suffered crown damage ≥75%, which suggests minimal potential for future mortality as a direct result of the Emerald Lake prescribed fire, given Methven's (1971) suggestion that mature white pine have a 50% chance of surviving the loss of three quarters of their foliage.

Logistic regression models indicate increasing probability of postfire white pine mortality and increasing probability of crown damage to surviving trees with decreasing DBH and increasing fire intensity, as measured by HSB. The predictive value of tree DBH in the model is consistent with most models of postfire tree mortality, which typically include either DBH (Bevins 1980; Wyant et al. 1986; Brown and DeByle 1987; Saveland and Neuenschwander 1990; Regelbrugge and Smith 1994; Mutch and Parsons 1998; Linder et al. 1998; Guinto et al. 1999) or bark thickness (Harmon 1984; Peterson and Arbaugh 1989; Ryan and Reinhardt 1988) as prominent predictive variables. DBH is related to white pine bark thickness and associated resistance to fire damage (Harmon 1984; Hengst and Dawson 1994). White pine DBH is an easily measured correlate of white pine bark thickness and associated resistance to fire damage (Harmon 1984; Peterson and Arbaugh 1989; Ryan and Reinhardt 1988) as prominent predictive variables. DBH is related to white pine bark thickness and associated resistance to fire damage (Harmon 1984; Hengst and Dawson 1994). White pine DBH is an easily measured correlate of tree height \(R^2 = 0.75, p < 0.001\) and associated fire resistance, since the separation between the ground and the crown base increases with height, thus decreasing both the potential for crown scorch due to convective hot gases (Van Wagner 1973) and the potential for crown involvement in fire behaviour (Van Wagner 1965).

We used HSB to infer tree-specific fire intensity, and this variable was a second key determinant of both white pine mortality and extent of crown damage to surviving trees.
HSB was ≤0.5 m for more than 50% of white pine and 80.8% trees had an HSB of ≤3.0 m. Waldrop and Van Lear (1984) used char height as a substitute for flame length estimates of fire intensity, and ratios between flame length and char height have been reported as 1.8 for sustained spreading fires in aspen (Brown and DeByle 1987) and 1.7 for head fires in shortleaf pine (Pinus echinata Mill.) and loblolly pine (Pinus taeda L.) (Cain 1984). Observed flame lengths of 1–3 m in our study site during the prescribed fire correspond well to the mean HSB of 2.3 m.

Weber et al. (1987) reported a strong correlation between mean char height and fire intensity in jack pine; however, a generalized model for relating fire intensity to char height has yet to be developed. Wood is known to discolor and char at temperatures >200–250°C (Drysdale 1998), and white pine bark ignites when exposed to 300°C for 69 s (Chandler et al. 1983). To infer flame height and associated fire intensity from HSB, a model of flame temperature as a function of height above ground is necessary. Yih (1953) presented a relationship for turbulent plumes above line sources of heat that was used by Van Wagner (1973) to model the relationship between height of crown scorch and fire intensity. Yih’s (1953) model is only applicable at heights adequate enough to reduce fire to an approximate line source (Weber et al. 1995) and is therefore insufficient for inferring fire intensity from HSB, which is much lower to the ground than scorch height. Weber et al. (1995) presented a model of the maximum temperature as a function of the height above ground within and above a spreading forest fire; however, fuel-specific calibration is required before predictions can be made. According to Dickinson and Johnson (2001), it is not yet practical to predict forest fire flame temperatures, and due to the lack of empirical flame temperature models, specific fire intensity could not be predicted from the HSB measurements recorded for individual trees.

Surprisingly, DFCB and the presence or absence of coarse woody debris, which are indicators of fuel characteristics, both failed to figure prominently in the model of probability of mortality for individual trees and the model of probability of crown damage levels for surviving trees. Site conditions influenced by the Knife Lake shoreline may have limited the explanatory potential of DFCB. Sample points were located along transects that were limited to the north by the edge of continuous blowdown and to the south by the Knife Lake shoreline. Significantly lower average DBH (cm) (Wilcoxon rank sum test, $p = 0.001$) in the ≥200 m distance class (Fig. 7) as compared with <200 distance classes indicated that white pine closest to the Knife Lake shoreline were more susceptible to fire damage. This suggests a shoreline edge effect, possibly due to previous disturbance such as logging. Increasing mortality at distances ≥150 m may also reflect increased wind exposure associated with shoreline proximity, which may have increased fire behaviour, as suggested by median HSB by distance class (Fig. 7). These results suggest that a measure of the distance from the nearest edge (i.e., blowdown or shoreline) would have been more effective at capturing potential variations in fire impacts and behaviour associated with these site conditions.

Presence of coarse woody debris within 1 m of tree stems significantly increases the risk of fire damage to some tree species, such as karri (Eucalyptus diversicolor) (McCaw et al. 1997). Results of this analysis suggest that status (presence or absence) of coarse woody debris within 1 m of the stem may not be a useful indicator of fuel characteristics and associated fire intensity in white pine stands, given certain weather conditions. This variable was not effective at capturing potential prefire litter accumulation that may have resulted due to the July 1999 windstorm. Log debris status could conceivably become an important factor in predicting white pine mortality and crown damage under elevated drought conditions, during which coarse woody debris...
would facilitate sustained smouldering and associated bole damage. A more robust measure of fuel characteristics, independent of weather conditions, would require fuel sampling around each sample tree prior to prescribed fire and would not be applicable to assessments of unplanned wildfire events.

Failure of visible bole damage to contribute to predictions of white pine mortality or to the probability of crown damage to surviving trees indicates that the study site slope effect on fire residence time was not a significant contributor to white pine mortality. With a buildup index of 23 and a drought code of 238 (Table 2), sustained smouldering was inhibited by fuel moisture levels, and combined with significant precipitation within 48 h postignition, this resulted in minimal potential for visible bole damage, despite the sloping terrain.

Results of this analysis indicate that DBH and HSB are key determinants of postfire white pine mortality. This study corroborates existing evidence that mature white pine are resistant to intense surface fire (1200 kW/m) and may be of practical importance for predicting the impact of future prescribed burns.

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References


