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# Predicting mortality of ponderosa pine regeneration after prescribed fire in the Black Hills, South Dakota, USA

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**Abstract.** Reduction of crown fire hazard in *Pinus ponderosa* forests in the Black Hills, SD, often focuses on the removal of overstorey trees to reduce crown bulk density. Dense ponderosa pine regeneration establishes several years after treatment and eventually increases crown fire risk if allowed to grow. Using prescribed fire to control this regeneration is hampered by the limited knowledge of fire-related mortality threshold values for seedlings (<1.4 m tall) and saplings (0.25 to 10 cm diameter at breast height). The present study was initiated to assess fire-related mortality of ponderosa pine seedlings and saplings on prescribed burns across the Black Hills. We established plots in several burn units after the first post-fire growing season to measure crown volume scorch, crown volume consumption, basal scorch, and ground char for ponderosa pine seedlings and saplings. Logistic regression was used to model the probability of mortality based on tree size, flame length, and direct fire effects. Tree size, flame length, crown damage, ground char, and basal char severity were all important factors in the prediction of mortality. Observed mortality was >70% for seedlings but was only 18 to 46% for sapling-sized trees. The differences in mortality thresholds for ponderosa pine seedlings and saplings highlight their susceptibility to different damage pathways and give managers several options when designing burn prescriptions.

**Additional keywords:** basal char, crown damage, fire management, ground char, logistic regression, *Pinus ponderosa*, saplings, seedlings.

## Introduction

Reduction of crown fire hazard in ponderosa pine (*Pinus ponderosa* var. *scopulorum* Dougl. ex Laws.) forests of the western United States often focuses on the removal of overstorey trees to reduce canopy bulk density. Although the initial treatment may reduce crown fire risk in the short term, the long-term outcome of these treatments is unknown. For instance, retention of a low-density mature overstorey coupled with ground disturbance can create ideal conditions for prolific regeneration (Oliver and Ryker 1990; Shepperd and Battaglia 2002) and produce rapid growth of new or existing pine regeneration (Fajardo *et al*. 2007). Ladder fuels and increased canopy density created over time by growth of these trees and the existing overstorey lead to increased potential for crown fire behavior. Therefore, sustaining forest structures that are more resilient to crown fire will require maintaining ponderosa pine seedling regeneration at low densities. Prescribed fire may be used to achieve this goal; however, the severity of direct fire effects needed to induce specific levels of seedling and sapling mortality is unknown. The ability to predict individual tree mortality in large ponderosa pine trees has been well studied (Wyant *et al*. 1986; Saveland and Neuenschwander 1990; Regelbrugge and Conrad 1993; Stephens and Finney 2002; McHugh and Kolb 2003; Keyser *et al*. 2006; Sieg *et al*. 2006; Thies *et al*. 2006). In contrast, fire-induced mortality threshold values for ponderosa pine seedlings (<1.4 m tall) and saplings (0.25 to 10 cm diameter at breast height, DBH) are limited (Harrington 1987, 1993; van Mantgem and Schwartz 2004).

In the Black Hills of South Dakota, favorable growing conditions and good seed crops often coincide and result in abundant natural ponderosa pine regeneration establishment, often exceeding 1000 stems $ha^{-1}$ (Shepperd and Battaglia 2002; Battaglia 2007). Historically, the density of this natural regeneration was regulated by wildfires every 10 to 35 years (Brown and Sieg 1996, 1999; Brown *et al*. 2000; Brown 2003; Wienk *et al*. 2004), resulting in a landscape that was a mosaic of multi-cohort patches of various densities and structure types (Brown and Cook 2006). However, the suppression of wildfires over the past century and the cost associated with mechanical thinning has led to ponderosa pine forests in the Black Hills that have dense thickets of seedling- and sapling-sized trees in the understorey (DeBlander 2002). The application of prescribed fire could potentially be used in the Black Hills to reduce regeneration density as it has been used to thin dense young stands in several other pine ecosystems (Morris and Mowat 1958; Wooldridge and Weaver 1965; Harrington 1987, 1993; Waldrop and Lloyd 1988).

Ponderosa pine seedlings and saplings should be more susceptible to low-intensity prescribed fires because they have thinner bark and lower crowns than their larger-diameter counterparts (van Mantgem and Schwartz 2003). These two factors increase the probability of multiple fire-induced injuries. The

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cumulative effect of these injuries to the foliage and cambium is thought to contribute to small tree mortality (van Mantgem and Schwartz 2004).

Low crown base heights increase the probability of crown scorch and consumption during a fire owing to the proximity of the foliage to the flame (van Wagtendonk 1983). Several studies in ponderosa pine trees >5 cm DBH have demonstrated a strong positive relationship between crown damage by fire and subsequent mortality (Wyant *et al*. 1986; Harrington 1987, 1993; Regelbrugge and Conrad 1993; Stephens and Finney 2002; McHugh and Kolb 2003; van Mantgem and Schwartz 2004; Keyser *et al*. 2006; Sieg *et al*. 2006; Thies *et al*. 2006). Other studies have shown that, in general, larger-diameter ponderosa pine trees can survive proportionally greater crown damage than smaller trees (Lynch 1959; Wyant *et al*. 1986; Harrington 1987, 1993; Stephens and Finney 2002; McHugh and Kolb 2003; Keyser *et al*. 2006; Sieg *et al*. 2006). The mortality thresholds associated with crown damage in these studies were often dependent on tree diameter, bark thickness, pre-fire vigor, crown ratio, and the presence or absence of other fire-related injuries.

Heat damage from flaming and smouldering combustion to basal cambial tissue is also an important factor to consider (Peterson and Arbaugh 1986, 1989; Ryan *et al*. 1988; Ryan and Frandsen 1991; Stephens and Finney 2002). Bark thickness and thermal resistance combined with fire intensity and duration determine the extent of cambium damage (Ryan and Frandsen 1991; van Mantgem and Schwartz 2003). Although small-diameter (<15 cm DBH) ponderosa pine trees possess some bark thermal resistance (van Mantgem and Schwartz 2003), fire-related cambial damage in these small trees has been associated with post-fire mortality (Lynch 1959; Wyant *et al*. 1986; Stephens and Finney 2002; McHugh and Kolb 2003; van Mantgem and Schwartz 2004; Keyser *et al*. 2006; Thies *et al*. 2006). Including cambial damage with crown injury has improved mortality models (Wyant *et al*. 1986; Stephens and Finney 2002; McHugh and Kolb 2003; Thies *et al*. 2006).

Heating of the soil from surface fuel and forest floor consumption can also damage the fine root system (Frandsen and Ryan 1986; Dumm 2003; Smith *et al*. 2004; Hart *et al*. 2005) and contribute to tree mortality (Swezy and Agee 1991; Stephens and Finney 2002). In areas where duff is completely consumed by fire, heat pulses into the upper layers of the mineral soil can reach temperatures lethal to roots and soil biota (Hartford and Frandsen 1992). Because root damage is inherently difficult to assess without excavation (Ryan 1982; Swezy and Agee 1991), the amount of charred ground is often used as a surrogate measure (Ryan and Noste 1985). However, the utility of these metrics has not been well established with small trees. Measures of ground char severity or fuel consumption in conjunction with other damage variables (crown and cambial damage) have been shown to either enhance (Swezy and Agee 1991; Stephens and Finney 2002; Sieg *et al*. 2006) or be insignificant in (McHugh and Kolb 2003; Thies *et al*. 2006) the prediction of mortality in ponderosa pine trees >5 cm DBH.

Use of prescribed fire to reduce ponderosa pine seedling and sapling densities requires specific knowledge of fire-induced mortality thresholds and predictive models developed using empirical data from these size classes. Most ponderosa pine mortality models were developed using data collected from trees >5 cm DBH with datasets that had average diameters exceeding 20 cm DBH. Use of these models to predict seedling and sapling mortality under prescribed burning conditions can produce erroneous predictions (Hood *et al*. 2007). Giving managers the ability to accurately predict regeneration mortality will allow the development of burn prescriptions to meet specific density reduction objectives and greatly enhance the ability to maintain specific forest conditions through time.

The objectives of the research reported here were to (1) develop logistic regression models to predict post-fire mortality of ponderosa pine seedlings and saplings in the Black Hills, and (2) identify factors that contribute to fire-induced mortality of these small trees. Providing these tools will greatly enhance the application of prescribed fire in the Black Hills ponderosa pine ecosystem and potentially save critical funds currently devoted to mechanical treatment of fuels and stocking control by lengthening the effectiveness of fuels treatments.

## Methods

### *Study sites*

The Black Hills are an isolated forested geologic uplift located in south-west South Dakota and north-east Wyoming that extends 200 km from north to south and 100 km from east to west (Shepperd and Battaglia 2002). Elevations in the Black Hills range from 1000 to 2207 m and are ∼300 to 1200 m above the surrounding Great Plains. The increased elevation results in an orographically induced microclimate that increases precipitation. Annual average precipitation ranges from 41 cm in the south to 74 cm in the north. Most of the precipitation occurs from April to August, with May and June receiving 33% of annual precipitation (Driscoll *et al*. 2000). Annual average temperature ranges from 2.9 to 9°C. The frequent rain showers during the early growing season in combination with warm temperatures are conducive to prolific natural ponderosa pine regeneration (Shepperd and Battaglia 2002). Ponderosa pine dominates 85% of the forested land base (DeBlander 2002) and is found at all elevations, soil types, and aspects. It can be found mixed with white spruce (*Picea glauca* [Moench] Voss) and aspen (*Populus tremuloides* Michx.) in the moister, higher elevations.

The present study was conducted within the Black Hills National Forest, Wind Cave National Park, and Mt Rushmore National Monument public lands (Table 1). We measured post-fire mortality of ponderosa pine seedlings and saplings on five dormant-season prescribed fires (Bullock, Buffalo, Horse Nugget, Medicine, and Rankin Tower) and one dormant-season wildfire (Lafferty Gulch). Sampling was restricted to dormant-season burns because prescribed burning in the Black Hills is limited to this time period for logistical and safety reasons. We recognize that mortality thresholds are likely sensitive to the physiological state of a tree as demonstrated by Harrington (1987, 1993). In those studies, higher mortality was observed in growing-season *v.* dormant-season fires for similar levels of crown scorch. However, from a practical standpoint, models to predict mortality during prescribed fires should be parameterized for conditions when these burns are likely to occur, when trees are in a dormant physiological state.

Prescribed burns were carried out within the burn prescription and were representative of operational burns for the Black Hills

**Table 1. Stand characteristics for sampled prescribed fires and wildfire**

Stands were dominated by ponderosa pine (*Pinus ponderosa*). Surface fuel models refer to the Anderson fire behavior models (1982). Values in parentheses are standard error of the means for seedling (<137 cm tall) and sapling (0.25 to 10 cm diameter at breast height, DBH) density. TPH, trees per hectare

| Fire | Latitude, longitude | Size (ha) | Elevation (m) | Surface fuel model | Overstorey DBH range (cm) | Seedling density (TPH) | Sapling density (TPH) |
|---|---|---|---|---|---|---|---|
| Bullock | 44°00′N, 103°32′W | 1000 | 1600 | 1, 9 | 15 to 41 | 2865 (1522) | 962 (496) |
| Buffalo | 44°07′N, 103°32′W | 182 | 1640 | 2, 9 | 15 to 41 | N/A[A] | N/A[A] |
| Lafferty Gulch | 43°53′N, 103°26′W | 39 | 1400 to 1450 | 2, 9 | 15 to 41, some up to 60 | 174 (132) | 334 (114) |
| Horse Nugget | 44°01′ to 44°03′N, 103°34′W | 600 | 1630 to 1770 | 2, 9, 11 | 15 to 41 | 1210 (476) | 521 (105) |
| Medicine | 43°56′N, 103°42′W | 728 | 1900 to 1975 | 1, 2 | 15 to 41 | 40 935 (9948) | 0 |
| Rankin Tower | 43°37′N, 103°28′W | 500 | 1400 to 1480 | 1, 2 | 15 to 41 | 6143 (1466) | 294 (83) |

[A]The study design for the Buffalo burn unit was not a random sample of regeneration density for the area.

(Table 2). The goals of these burns are often to reduce surface and ladder fuels, stimulate browse species, encourage grass and forb production, and create openings. Operational burns were ignited with hand-carried drip torches to produce multiple-strip head fires spaced to yield flame lengths that ranged between 0.15 and 1.5 m tall. Acceptable weather conditions to remain in prescription include: maximum temperature of 16°C; minimum relative humidity of 15–25%; maximum wind speeds of 8 km $h^{-1}$; and minimum fuel moisture based on fuel particle size: 1-h fuel moistures of 4–10%; 10-h fuel moistures of 7–10%; and 100-h fuel moistures of 9–13%. The Lafferty Gulch wildfire began as a result of a pile burn operation on 26 February 2006 and burned until 3 March 2006. Although it was classified as a wildfire, weather conditions and fire intensity (bole char heights up to 7.5 m) during the wildfire were similar to those of other prescribed burns (Table 2).

Sampling was limited to fires that occurred within 4 to 8 months of the following growing season to ensure fire-related damage measurements were captured before needles abscized or understorey vegetation recovery made it difficult to determine ground severity.

### *Plot setup*

Although sample design and layout differed between the sites, plot sampling procedures were similar. The design and layout differed because the Medicine and Buffalo burns, which occurred in fall (autumn) 2004 and fall 2006, respectively, were part of a separate study to investigate the relationship between fire behavior and regeneration mortality. Random plots were established before the prescribed burn to measure fire behavior and remeasured one growing season after the fire. The other four sites in the current study were established within one growing season after the fire and measured from a random starting point.

### *Medicine and Buffalo prescribed fires*

We established 25 randomly located plots within the Medicine burn unit. Fire behavior was monitored during the 19 October 2004 prescribed fire using a video camera and flame heights were estimated for 15 of the 25 plots. At each plot, a post with 0.15-m intervals was used as a reference point to measure flame height. Flame height (H, m) was converted to flame length (L, m) using the following equation:

$$L = [H(\sin(90 - \beta))]/(\sin(\theta - \beta)) \quad (1)$$

where β is the measured slope angle and θ is the angle of the flame from the horizontal. A mean flame angle of 50° was used for the conversion in Eqn 1 following Kobziar *et al*. (2006).

We established twenty 20.25-$m^2$ square plots within the Buffalo burn unit in July 2005. Fire behavior and sapling mortality were observed within a nested 12.25-$m^2$ (3.5 × 3.5 m) subplot. On 15 of the 20 subplots, fire behavior was recorded with a video camera during the 1 November 2006 burn. At each subplot, a post with 0.15-m intervals was used as a reference point to measure flame height. Flame height (H, m) was converted to flame length (L, m) using Eqn 1 following Kobziar *et al*. (2006).

**Table 2. Ranges of fire weather data for each day of the prescribed fires and wildfire obtained from spot forecast or local remote access weather stations (RAWS)**

| | Medicine | Rankin Tower | Horse Nugget | Bullock | Buffalo | Lafferty Gulch |
|---|---|---|---|---|---|---|
| Date | 19 October 2004; 18 November 2004 | 25 October 2005 | 28 October 2005; 1–2 November 2005 | 24 January 2006 | 1 November 2006 | 26 February 2006 to 3 March 2006 |
| Air temperature (°C) | 5.5 to 11 | 15.5 to 18.8 | 13.3 to 19.4 | 7.2 to 10.5 | −4 to 0.5 | −0.5 to 8.9 |
| Relative humidity (%) | 29 to 48 | 21 to 30 | 24 to 40 | 26 to 33 | 27 to 34 | 31 to 48 |
| Wind speed ($km\ h^{-1}$) | 4.8 to 11.2 | 1.6 to 8.1 | 0 to 12.9 | 3.2 to 4.8 | 3 to 11 | 1.6 to 8.1 |
| Wind gusts ($km\ h^{-1}$) | 16.1 to 24.1 | N/A | 9.7 to 38.6 | 27.4 | 32 | 25.8 |
| 10-h fuel moisture (%) | 9 to 12 | 6 to 8 | 8 to 12 | 9 to 10 | 8 to 9 | 6 to 7 |
| Source | Spot forecast | RAWS[A] | RAWS[B] | RAWS[B] | RAWS[B,C] | RAWS[D] |

[A]43°33′N, 103°29′W.
[B]43°52′N, 103°27′W.
[C]44°11′N, 103°30′W.
[D]43°03′N, 103°34′W.

For both fire behavior observational studies, fires were ignited with hand-carried drip torches to produce multiple-strip head fires throughout the burn unit.

### *Rankin Tower, Bullock, and Horse Nugget prescribed fires*

Transects 200 m long were established on the Bullock, Horse Nugget, and Rankin Tower burn units in the 2006 growing season, 4 to 8 months after fire. The starting point of each transect was randomly generated within the Bullock ($n = 1$) and Horse Nugget ($n = 5$) prescribed burn perimeters. In the Rankin Tower prescribed burn, the starting point of two transects were placed on permanent monitoring plots that were already established by Wind Cave National Park staff, whereas the other three transects were randomly established. The direction of each transect was randomly chosen and a plot ($n = 5$ per transect) was established every 50 m along each transect within a burn unit.

### *Lafferty Gulch wildfire*

Before the wildfire, the Lafferty Gulch area had been mechanically thinned in 2003 to remove ponderosa pine saplings <15 cm DBH. Most of the residual slash had been piled and burned (which incidentally started the wildfire). Originally, the National Park Service staff had set up randomly selected plots within the project area to monitor impacts of thinning. Several of these original monitoring plots burned in the wildfire and we utilized four of these plots as a starting point for four transects. The direction of each transect was randomly chosen and a plot ($n = 5$ per transect) was established every 50 m along each transect. An additional seven fire mortality plots were established at the location of other original fuel reduction project monitoring plots within the burn perimeter.

### *Data collection*

A nested plot design consisting of a 2-m radius circular plot to sample ponderosa pine seedlings (trees <137 cm tall) located within a larger circular plot to sample saplings (trees 0.25 to 10 cm DBH) was used on all sites except the Buffalo study site. The larger sapling plot was 5 m in radius on the Medicine site and 15 m in radius on the Rankin Tower, Bullock, Horse Nugget, and Lafferty Gulch study sites. We increased the radius size for the Rankin Tower, Bullock, Horse Nugget, and Lafferty Gulch because it was found that a 5-m radius on the Medicine burn did not include enough saplings. Ponderosa pine seedlings were categorized into five height size classes (0.1 to 15.2 cm; 15.2 to 45.7 cm; 45.7 to 76.2 cm; 76.2 to 106.7 cm; and 106.7 to 137 cm). We categorized ponderosa pine saplings into five diameter size classes (0.25 to 2.54 cm; 2.54 to 5.1 cm; 5.1 to 7.6 cm; 7.6 to 10.2 cm; and 10.2 to 12.7 cm). Seedling and sapling density, status (live or dead), and fire-related damage were assessed on each of the seedling and sapling plots (Table 3). Trees were considered dead when there were no live buds present.

Fire damage variables were measured for each seedling and sapling on each plot. Percentage of pre-fire live crown volume scorched (CVS) and percentage of pre-fire live crown volume consumed (CVC) were visually assessed to the nearest 5% by viewing each tree from all sides (Peterson 1985). Crown scorch

**Table 3. Range of morphological and tree-injury measured data used to develop and calibrate seedling and sapling mortality models**

| | | Tree-injury models | | |
|---|---|---|---|---|
| Ground char severity | *n* | Height (cm) | Crown volume damage (%) | Basal char severity class |
| Seedling | | | | |
| Unburned | 478 | 7.6 to 122 | 0 to 100 | 0 to 4 |
| Light | 959 | 7.6 to 122 | 0 to 100 | 0 to 4 |
| Moderate | 118 | 7.6 to 122 | 25 to 100 | 0 to 4 |
| Consumed | 60 | 7.6 to 122 | 80 to 100 | 0 to 4 |
| Ground char severity | *n* | Diameter at breast height (cm) | Crown volume scorch (%) | Crown volume consumed (%) |
| Sapling | | | | |
| Unburned | 208 | 0.25 to 12.7 | 0 to 100 | 0 to 95 |
| Light | 1083 | 0.25 to 10.2 | 0 to 100 | 0 to 100 |
| Moderate | 792 | 0.25 to 12.7 | 0 to 100 | 0 to 100 |
| Consumed | 807 | 0.25 to 10.2 | 0 to 100 | 0 to 100 |
| Basal char severity class | *n* | Diameter at breast height (cm) | Crown volume scorch (%) | Crown volume consumed (%) |
| 0 | 902 | 0.25 to 12.7 | 0 to 100 | 0 to 100 |
| 1 | 35 | 0.76 to 10.2 | 0 to 100 | 0 |
| 2 | 63 | 0.25 to 10.2 | 0 to 100 | 0 to 40 |
| 3 | 305 | 0.25 to 10.2 | 0 to 100 | 0 to 95 |
| 4 | 1585 | 0.25 to 12.7 | 0 to 100 | 0 to 100 |
| | | Fire behavior models | | |
| Size class | *n* | Flame length (m) | Height (m) | Diameter at breast height (cm) |
| Seedling | 972 | 0.076 to 1.22 | 0.76 to 1.22 | N/A |
| Sapling | 415 | 0.1 to 1.4 | 1.4 to 7.3 | 0.25 to 12.7 |

was defined as foliage that experienced color change as a result of fire (Keyser *et al*. 2006), but which was not consumed (Ryan 1982). This included singed foliage as defined by McHugh and Kolb (2003). Crown consumption was defined as foliage consumed by active combustion and was determined by the presence of needle fascicles on small branches to indicate that branches had supported live foliage before the fire (McHugh and Kolb 2003; Sieg *et al*. 2006). Total crown volume damaged (CVD) was calculated by adding CVS + CVC (McHugh and Kolb 2003; Sieg *et al*. 2006).

Basal char severity was used to estimate cambial damage based on the criteria established by Ryan (1982) and utilized by several recent studies (McHugh and Kolb 2003; Sieg *et al*. 2006; Thies *et al*. 2006; Hood and Bentz 2007). The percentage of the basal circumference on the first 5 cm above the ground was assessed with the following criteria: 0 = unburned, no evidence of flame having contacted the bole and no charring or darkening of the bole; 1 = light, light scorch or char on edges of bark plates; 2 = moderate, bark is uniformly black with the possible exception of the inner depths of the prominent fissures, but bark character is still discernable; 3 = deep, bark is deeply charred, but not necessarily to the wood and surface characteristics have been lost. We assumed that heat sufficient to cause moderate or deep basal char would kill the cambium (Thies *et al*. 2006). A basal char severity class was calculated by summing the percentage of the bole with moderate or deep basal char. Basal char severity classes (BC) were: 0 = no moderate or deep basal char; 1 = summation of moderate and deep basal char was $>0$ and $<25\%$; 2 = summation of moderate and deep basal char was $>25$ and $<50\%$; 3 = summation of moderate and deep basal char was $>50$ and $<75\%$; and 4 = summation of moderate and deep basal char was $>75\%$.

Ground surface char severity was used to indirectly estimate damage to root systems (Swezy and Agee 1991; McHugh and Kolb 2003; Sieg *et al*. 2006; Thies *et al*. 2006; Hood and Bentz 2007). The dripline of seedling or sapling crown was divided into quadrants and ground char (GC) was measured in each quadrant using the criteria developed by Ryan (1982): 0 = unburned, no visible effect on soil; 1 = light, surface of litter and duff layers scorched or charred but duff is not significantly altered; 2 = moderate, litter completely consumed and duff deeply charred; 3 = consumed, litter and duff completely consumed, ash only can be seen but the underlying mineral soil is not altered. A ground-char severity index was calculated as the sum of the four quadrant codes divided by four.

Because we were unable to observe the fire behavior in the Rankin Tower, Bullock, Horse Nugget, and Lafferty Gulch burn units, we estimated flame lengths based on bole scorch height (Cain 1984; Brown and DeByle 1987). Bole scorch height was measured on four randomly selected overstorey trees at each plot within a burn unit and averaged. Based on observed flame lengths and measured bole scorch heights ($n = 400$ trees) from the Buffalo burn unit, we calculated a flame length : bole scorch height ratio. We multiplied this ratio (1.2) by the average bole scorch height to obtain a predicted flame length.

### *Data analysis*

Data from each fire were pooled to test for difference between live and dead trees morphological and fire-damage characteristics. Wilcoxon rank sum tests were used to test for these differences ($\alpha = 0.05$) using the *NPAR1WAY* procedure in SAS (SAS Institute 2001). We assessed differences in average mortality by size class using *PROC Mixed* in SAS (SAS Institute 2001) with 'burn unit' as a random variable.

We used logistic regression models to develop models that predict the probability of seedling or sapling mortality within the first post-fire growing season. These models are useful for predicting the probability of an occurrence (i.e. live or dead tree), based on predictor variables such as crown damage or tree size. Also, logistic regression analysis does not require normally distributed values. Logistic regression analysis is an accepted technique to model fire-related mortality and has been successfully used for predictions in prescribed burn (Ryan and Reinhardt 1988; Ryan and Frandsen 1991; Harrington 1993; Stephens and Finney 2002; McHugh and Kolb 2003; Thies *et al.* 2006) and wildfires (Regelbrugge and Conrad 1993; Keyser *et al.* 2006; Sieg *et al.* 2006). The logistic regression equation used to model tree mortality has the form:

$$P(\mathrm{m}) = 1/[1 + \exp(-(\beta_0 + \beta_1 X_1 + \ldots + \beta_n X_n))] \qquad (2)$$

where $P$(m) is the predicted probability of tree mortality, $\beta_0$, $\beta_1$, and $\beta_n$, are regression coefficients, and $X_1$ and $X_n$ are representative independent variables. The logistic function provides a continuous estimate of the probability of mortality between zero and one, with one indicating a dead tree. We used a cutoff of 0.5 to signal mortality (Saveland and Neuenschwander 1990; Keyser *et al.* 2006). If $P(\mathrm{m}) < 0.5$, then the tree was predicted live, otherwise it was predicted dead.

### *Fire-damage mortality models*

*PROC LOGISTIC* was also used to predict mortality based on tree morphological and fire-damage variables from the Medicine, Rankin Tower, Bullock, Horse Nugget, and Lafferty Gulch study sites. Only variables that were significantly different between live and dead trees ($P < 0.05$) and were not strongly correlated ($r \leq 0.50$) with other independent variables were used in the development of logistic regression models (McHugh and Kolb 2003; Thies *et al.* 2006). Separate models were developed for seedlings and saplings because the tree morphological measurement that differed by convention defines the two size classes (i.e. seedlings = height and saplings = DBH). Exploratory models using the tree morphological and fire damage variables were developed using score and stepwise selection options (Hosmer and Lemeshow 2000). All independent variables and any biologically relevant interactions were included in the full model. The generalized Wald statistic with a $\chi^2$ distribution was used to test if model coefficients were different from zero ($\alpha = 0.05$). Only variables and interactions that were found to have a $P$-value $<0.05$ were kept in the model.

Models were built using a random sample of ~75% of the full data. The prediction capacity of significant models was assessed using the remaining ~25% of the full dataset to validate the models (Regelbrugge and Conrad 1993; Keyser *et al.* 2006). The Hosmer–Lemeshow goodness of fit test was used to evaluate the fit of the final models (Hosmer and Lemeshow 2000). A Hosmer–Lemeshow test statistic with $P > 0.05$ indicates a good fit and that the model prediction does not significantly differ from the observed data. We also used the receiver operating characteristic (ROC) curve analysis (Saveland and Neuenschwander 1990; Hosmer and Lemeshow 2000) to evaluate the model's ability to discriminate between dead and live trees. Models with ROC values between 0.70 and 0.80 have acceptable discrimination, ROC values between 0.80 and 0.90 have excellent discrimination, and ROC values $\geq$0.90 have outstanding discrimination (Hosmer and Lemeshow 2000). Final models were developed with generalized estimating equations (GEE) in *PROC GENMOD* in SAS (SAS Institute 2001) to account for autocorrelated data within each transect (Sieg *et al.* 2006). For each model, we used the validation dataset to assess the model's prediction to the observed status of the tree and calculated the percentage of correctly classified trees. In addition, as the Buffalo burn data was not used to develop the fire-damage mortality models, we used these data as an external model validation dataset for the fire-damage mortality models.

To ensure the developed models were applicable across the Black Hills, we performed an additional analysis that included a categorical 'location' variable to assess if this variable added significantly to the model's ability to predict tree mortality. Development of these models followed the same procedures described above. If location was significant, this would indicate that pooling of the data would be inappropriate for that specific model.

### *Fire-behavior mortality models*

We used the observed flame length data from the Medicine and Buffalo burn units to predict tree mortality using *PROC LOGISTIC* in SAS (SAS Institute 2001) following the same procedures and protocols as described above. Models were developed to predict mortality based on height for seedlings and saplings. An additional model was developed to predict mortality based on DBH for saplings.

## Results

### *Seedlings*

Of the 1619 seedlings surveyed, 78% were dead after the first growing season following fire. The percentage of seedlings that died decreased with seedling height (Fig. 1*a*). Mortality of seedlings less than 76 cm tall was above 90% (Fig. 1*a*). Mortality of seedlings that were 76 to 137 cm tall ranged from 50 to 60% (Fig. 1*a*).

Dead seedlings were significantly shorter than the surviving seedlings (Table 4). Dead and live seedlings had similar crown volume scorch values, but dead seedlings had significantly higher crown volume consumption and total crown damage than live seedlings (Table 4). Cambial injury, as measured by basal char severity, was significantly higher for dead seedlings (Table 4). Damage to roots, as measured by ground char severity, was significantly higher around dead seedlings (Table 4).

### *Logistic models for seedlings*

Many one- or two-variable models that managers could use more readily in the field were attempted, but the majority of them failed to pass the Hosmer–Lemeshow goodness of fit test or had low accuracy. Multivariate models that included seedling height, multiple fire damage variables, and flame height predicted mortality with the highest ROC values (0.97) and accuracy (94%) (Table 5). Basal char (BC) and ground char (GC) severity were not highly correlated ($r = 0.42$; $P < 0.0001$), so both were included as candidate variables during model development. Because there was no significant difference in crown volume scorch (CVS) between live and dead seedlings (Table 4), only total crown volume damage (CVD) was used as a crown damage variable during model development. Location was insignificant ($P > 0.05$) for each seedling model. For each of the significant models, coefficients for seedling height were negative, indicating that shorter seedlings have a significant increase in *P*(m) (Table 5). *P*(m) increased with increasing direct fire effects (CVD, BC, GC) (Table 5).

Levels of GC and BC severity influenced the amount of crown damage that was in turn associated with mortality (Fig. 2). Predicted mortality was more sensitive to GC severity than BC severity. For example, at similar levels of BC severity, the amount of CVD needed to kill seedlings decreased substantially with an increase in GC severity (Fig. 2). At similar levels of GC severity, the amount of CVD required to kill seedlings also decreased with an increase in BC severity, but at a slower rate (Fig. 2).

Observed fire behavior data from the Medicine prescribed burn was used to develop a model that predicted seedling mortality based on observed flame length (Table 5; ROC = 0.90, accuracy = 92%). The *P*(m) of seedlings increased with flame length (Fig. 3*a*). Dead seedlings (*P*(m) = 0.5) less than 60 cm tall were associated with flame lengths of 5 cm (Fig. 3*a*). In order to kill seedlings that were 90 cm tall, the model predicted flame lengths >25 cm were necessary and flame lengths >45 cm were necessary to kill seedlings that were 120 cm tall (Fig. 3*a*).

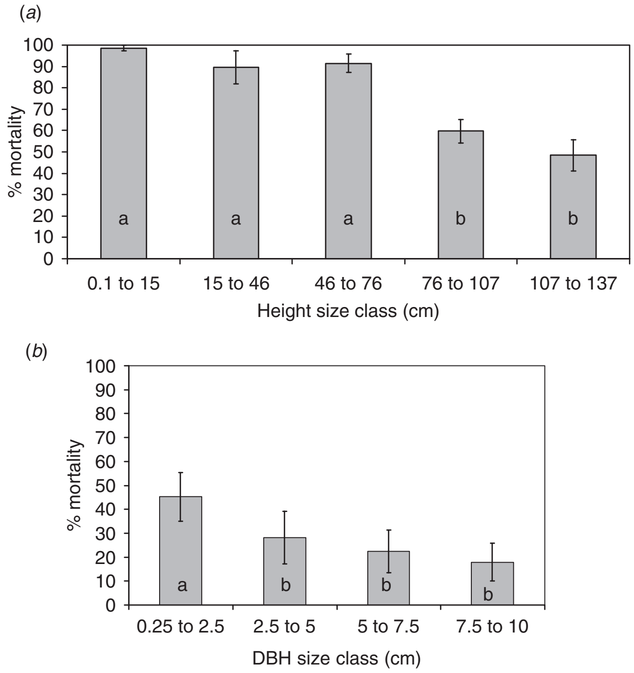


**Fig. 1.** Observed average percentage mortality (±s.e.m.) of ponderosa pine (*a*) seedlings (<137 cm tall) and (*b*) saplings after dormant season fire ($n = 6$) by size class (diameter at breast height, DBH). Significant differences ($P < 0.05$) among seedling size classes or sapling size classes were tested on the LSMEANS and are designated by different letters.

### *Saplings*

Of the 2890 saplings surveyed, 41% were dead in the first growing season following fire. The percentage of saplings that died ranged from 18 to 45%, with lower mortality occurring for larger diameters (Fig. 1*b*).

Dead saplings were significantly smaller in diameter than surviving saplings (Table 4). Fire injuries to the crown, bole, and cambium were significantly higher for dead saplings than live saplings (Table 4).

### *Logistic models for saplings*

Multivariate models that included sapling DBH, multiple fire damage variables and flame length predicted mortality with the highest ROC values and accuracy (Table 6). BC severity and GC severity were correlated ($r = 0.66$; $P < 0.0001$); therefore,

**Table 4. Mean characteristics of live and dead ponderosa pine seedlings (<137 cm tall) and saplings (0.25 to 10 cm diameter at breast height) after prescribed fires in the Black Hills of South Dakota**

The *P*-value shows results of Wilcoxon rank sum test. Hgt (cm) is seedling height; DBH (cm) is diameter at breast height; CVS, crown volume scorched; CVC, crown volume consumed; CVD, crown volume damage (scorch + consumption); GC, ground char severity class rating (0, unburned; 1, light; 2, moderate; 3, consumed); BC, basal char severity (%moderate + %deep) class rating (0, 0% basal char severity; 1, >0% and <25% basal char severity; 2, >25% and <50% basal char severity; 3, >50% and <75% basal char severity; or 4, 75% basal char severity)

| Variable | Seedlings ($n = 1619$) | | | Saplings ($n = 2890$) | | |
|---|---|---|---|---|---|---|
| | Live | Dead | *P* value | Live | Dead | *P* value |
| Hgt (cm) | 66.9 | 43.2 | <0.0001 | N/A | N/A | N/A |
| DBH (cm) | N/A | N/A | N/A | 4.3 | 3.1 | <0.0001 |
| CVS (%) | 43.1 | 50.7 | 0.2704 | 33.4 | 78.2 | <0.0001 |
| CVC (%) | 0.30 | 46.8 | <0.0001 | 0.18 | 17.3 | <0.0001 |
| CVD (%) | 43.4 | 97.5 | <0.0001 | 33.6 | 95.6 | <0.0001 |
| BC | 0.28 | 1.40 | <0.0001 | 1.9 | 3.5 | <0.0001 |
| GC | 0.42 | 0.97 | <0.0001 | 1.4 | 2.3 | <0.0001 |

**Table 5. Logistic regression coefficients, −2 log-likelihood ratio statistic (−2 LL), Hosmer-Lemeshow goodness of fit test statistic (H-L), receiver operating characteristic curve value (ROC), and overall rate of correctly predicted probability of mortality (*P*(m)) for ponderosa pine seedlings (<137 cm tall) following prescribed fires during the dormant season in the Black Hills of South Dakota**

Correctly predicted mortality was based on the validation dataset at a cutoff *P*(m) of 0.5. Model coefficients: regression coefficients are significant at *, $\alpha = <0.0001$; ‡, $\alpha = 0.009$; and †, $\alpha = 0.02$. Abbreviations for model coefficients are described in Table 4

| Model | Model (*n*) | Intercept | Hgt (cm) | CVD (%) | GC | BC | Flame length (cm) | −2 LL | H-L | ROC | Validation (*n*) | % correct |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. HGT, CVD, GC, BC | 1280 | −2.6868* | −0.0287* | 0.0553* | 1.3603* | 0.3271‡ | | 478.9 | 0.38 | 0.97 | 335 | 94 |
| 2. HGT, flame length | 739 | 2.7140* | −0.0363* | | | | 0.0408† | N/A | 0.35 | 0.90 | 233 | 92 |

separate regression models were created for each variable. As with seedlings, one or two variable models that managers could use more readily in the field were attempted, but again, the majority of them also failed to pass the Hosmer–Lemeshow goodness of fit test. For each of the significant models, coefficients for DBH were negative, indicating *P*(m) increased as sapling size decreased (Table 6). Coefficients for crown damage (CVS and CVC), BC severity and GC severity were all positive, suggesting that increases in these direct fire effects result in a greater likelihood of mortality (Table 6).

Models using DBH, CVC, CVS, and either GC severity or BC severity explained the most variation (ROC = 0.97) and had the highest accuracy (92%) of all the models developed (Table 6). These two models suggest that the effect of fire on ponderosa pine saplings is strongly linked to sapling size, crown damage, impacts to surface roots, and cambial damage. In general, the amount of crown damage required to kill saplings ($P(\mathrm{m}) \geq 0.5$) decreased as GC severity (Fig. 4) or BC severity (data not shown) increased. Mortality of smaller DBH saplings required lower values of crown damage and GC severity (Fig. 4) or BC severity (data not shown) than larger-diameter saplings. Furthermore, the type of crown damage (i.e. crown scorch or crown consumption) was an important factor to consider when predicting mortality because higher levels of crown consumption resulted in increased mortality. This mortality increased as GC severity (Fig. 4) or BC severity (data not shown) increased, with lower amounts of crown consumption required to predict mortality.

Using the fire behavior data from the Buffalo prescribed burn, we developed two separate models that predicted sapling mortality based on observed flame length and either sapling DBH or height. Both the DBH and height model had an ROC value of 0.87 and accuracies that exceeded 83% (Table 6). The *P*(m) of saplings increased with flame length, with longer flame lengths required to kill larger-diameter or taller saplings (Fig. 3*b*, *c*).

Predicted flame lengths for the other fires (Bullock, Horse Nugget, Lafferty Gulch, and Rankin Tower) ranged from 0.20 to 5.0 m and observed mortality increased with predicted flame length (Fig. 5). No sapling mortality was observed at flame lengths <0.40 m. Observed mortality in saplings >2.5 cm DBH exceeded 50% with flame lengths >0.80 m tall (Fig. 5), but for the >5.0-cm DBH saplings, flame lengths of 2.0 m were needed for any appreciable mortality (Fig. 5).

### *External model validation*

The sapling fire-damage mortality models performed well when the observed mortality Buffalo burn dataset was used. Of the 564 trees observed, 13% were dead after the first growing season. Using a *P*(m) value of 0.5, Model 1 (Table 6), which included BC severity, correctly classified 87% of the trees. The model correctly predicted 62% of the dead trees and 90% of the live trees. Model 2, which included GC severity, correctly classified 89% of the trees. The model correctly predicted 60% of the dead trees and 93% of the live trees.

## Discussion

Logistic regression analysis indicated that tree size (height or DBH), crown damage, GC severity, and BC severity were all important factors in predicting mortality. Model accuracy was

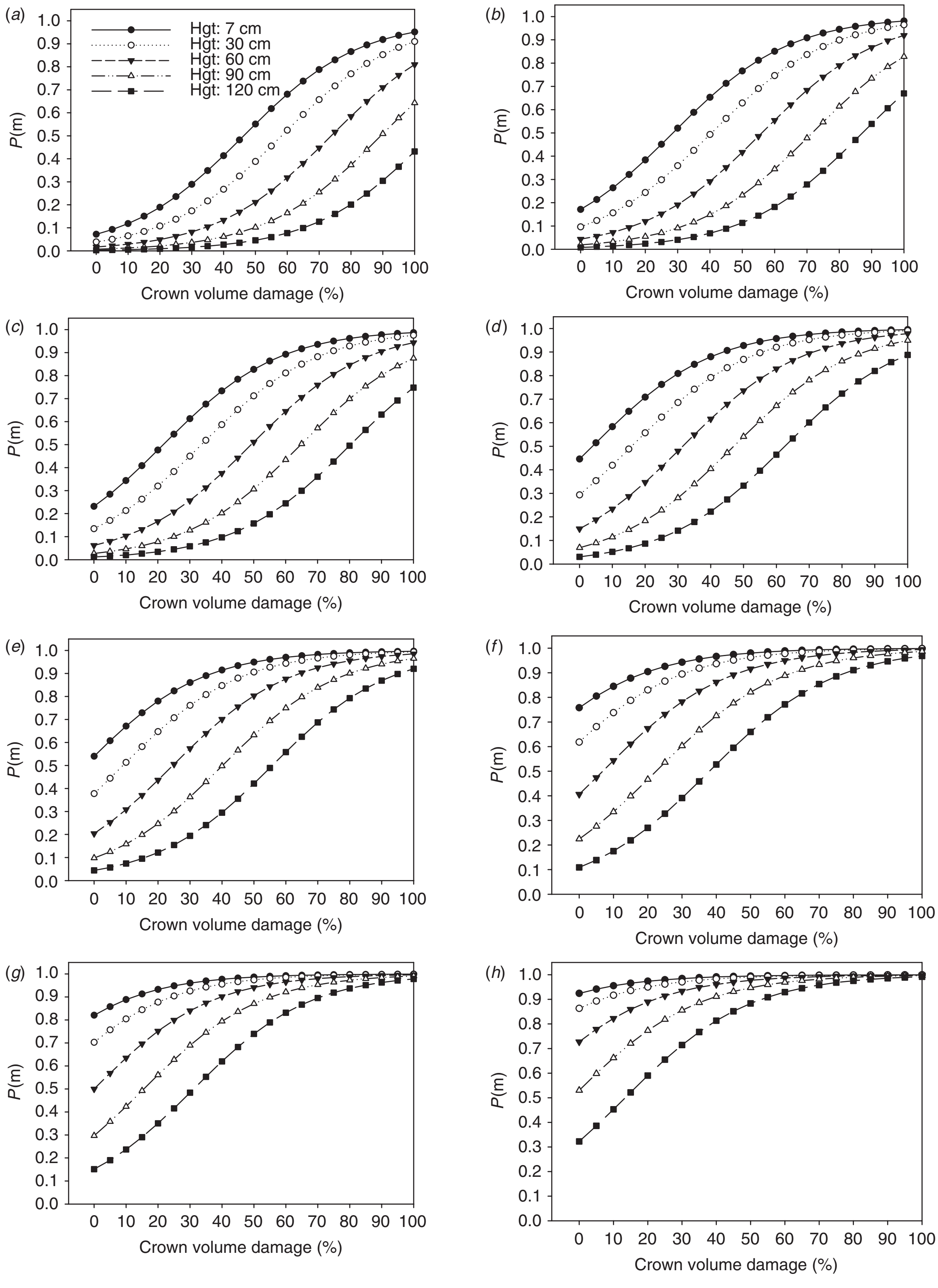


**Fig. 2.** Estimated mortality (*P*(m)) of ponderosa pine seedlings (<137 cm tall) predicted by crown volume damage, ground char severity, and basal char severity (Model 1, Table 5). Figures depict several combinations: (*a* and *b*) unburned ground char with (*a*) 0 to 25% basal char severity and (*b*) >75% basal char severity; (*c* and *d*) light ground char with (*c*) 0 to 25% basal char severity and (*d*) >75% basal char severity; (*e* and *f*) moderate ground char with (*e*) 0 to 25% basal char severity and (*f*) >75% basal char severity; (*g* and *h*) consumed ground char with (*g*) 0 to 25% basal char severity and (*h*) >75% basal char severity. Mortality was extrapolated for moderate ground char from crown volume damaged (CVD) 0 to 25% and consumed ground char from CVD 0 to 80%.

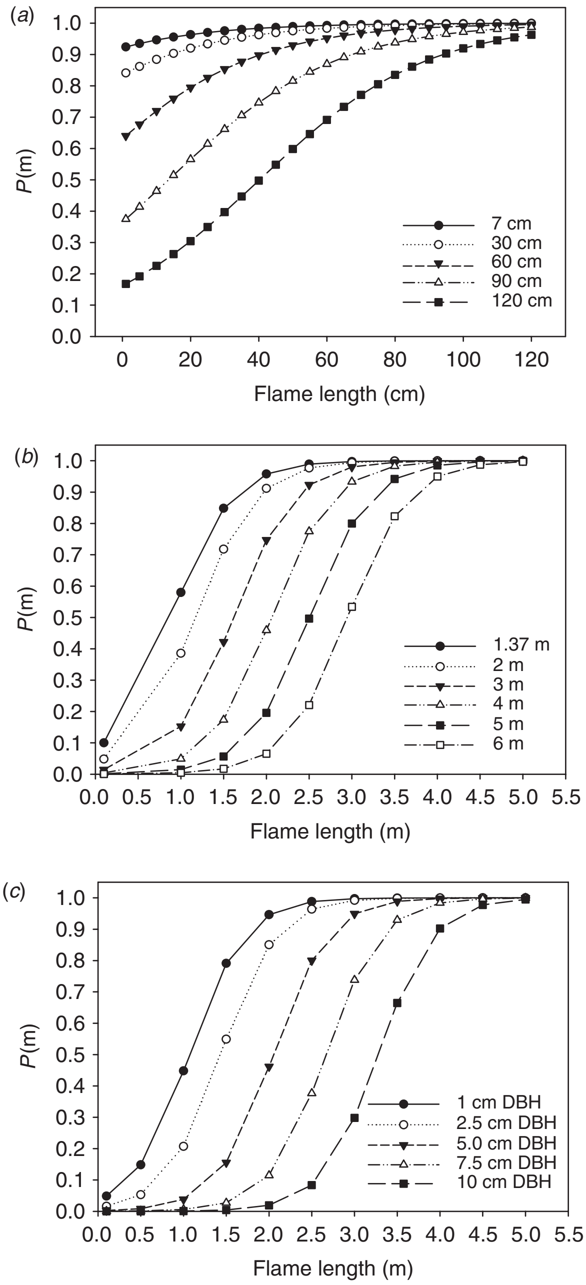


**Fig. 3.** Estimated mortality ($P$(m)) of (*a*) ponderosa pine seedlings (<137 cm tall) and (*b*) saplings (0.25- to 10-cm diameter at breast height, DBH) predicted by flame length and height (Model 2, Table 5; Model 4, Table 6) or DBH (Model 3, Table 6). Mortality was extrapolated for flame lengths exceeding 1.4 m for the sapling model.

highest with the inclusion of at least three of these variables, suggesting that small tree mortality is a result of multiple injuries. Burn unit was not significant in any of the fire-damage models and the models performed well on an additional burn unit not used for model development, indicating that these models are applicable throughout the Black Hills region. Understanding the mechanisms that promote fire-induced mortality in ponderosa pine regeneration will allow managers to more effectively plan

**Table 6. Logistic regression coefficients, −2 log-likelihood ratio statistic (−2 LL), Hosmer-Lemeshow goodness of fit test statistic (H-L), receiver operating characteristic curve value (ROC), and overall rate of correctly predicted mortality for ponderosa pine saplings (0.25 to 10 cm diameter at breast height, DBH) following prescribed or wildfires during the dormant season in the Black Hills of South Dakota**

Correctly predicted mortality was based on the validation dataset at a cutoff estimated mortality ($P$(m)) of 0.5. All regression coefficients are significant at $\alpha = <0.0001$. Abbreviations for model coefficients are described in Table 4

| Model | Model (*n*) | Intercept | DBH (cm) | Hgt (m) | CVC (%) | CVV (%) | GC | BC | Flame length (m) | −2 LL | H-L | ROC | Validation *n* | % correct |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. DBH, CVC, CVS, BC | 1763 | −7.8955 | −0.2102 | | 0.1435 | 0.0867 | | 0.5474 | | 828.3 | 0.24 | 0.97 | 573 | 92 |
| 2. DBH, CVC, CVS, GC | 1762 | −7.9876 | −0.2913 | | 0.1364 | 0.0844 | 1.219 | | | 796.1 | 0.07 | 0.97 | 573 | 92 |
| 3. DBH, flame length | 342 | −2.5319 | −0.7563 | | | | | | 3.0796 | N/A | 0.25 | 0.87 | 103 | 83 |
| 4. Hgt, flame length | 340 | −0.7661 | | −1.2487 | | | | | 2.7981 | N/A | 0.26 | 0.87 | 103 | 86 |

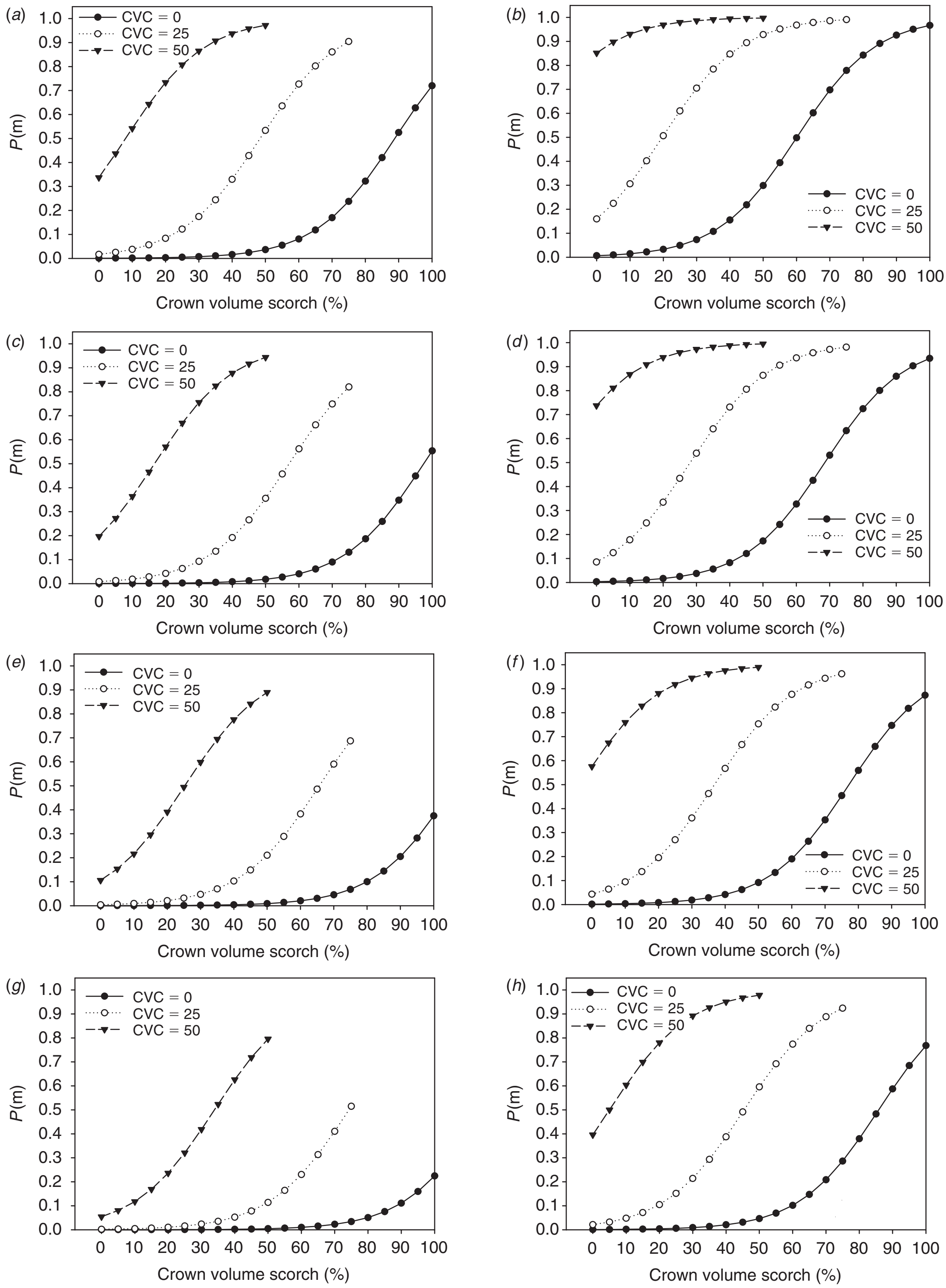


**Fig. 4.** Estimated mortality of ponderosa pine saplings predicted by crown volume scorch, crown volume consumption, and ground char severity (Model 2, Table 6). Figures depict several combinations: (*a* and *b*) 2.5-cm diameter at breast height (DBH) saplings with (*a*) light and (*b*) consumed ground char severity; (*c* and *d*) 5 cm DBH saplings with (*c*) light and (*d*) consumed ground char severity; (*e* and *f*) 7.5-cm DBH saplings with (*e*) light and (*f*) consumed ground char severity; (*g* and *h*) 10-cm DBH saplings with (*g*) light and (*h*) consumed ground char severity.

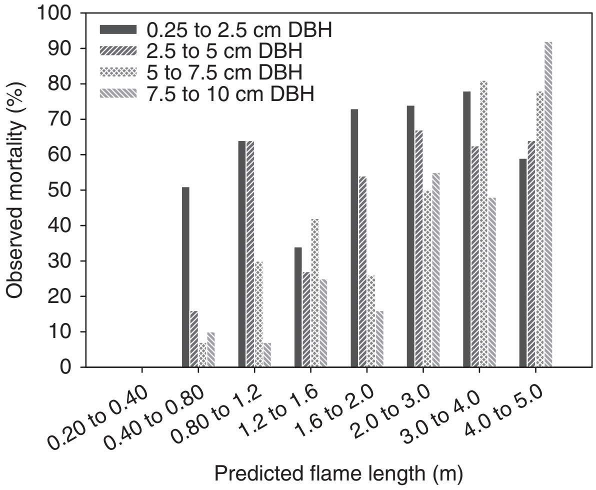


**Fig. 5.** Observed mortality of ponderosa pine saplings across several prescribed fires within the Black Hills of South Dakota. Flame lengths were predicted from average bole scorch heights on each plot.

prescribed fires and assess their success in meeting burn plan objectives.

Our survey of several prescribed fires and one dormant-season wildfire across the Black Hills indicates that dormant-season low-severity fire can be used to control ponderosa pine regeneration density without killing the overstorey. Under prescribed burning conditions, observed mortality was >90% for ponderosa pine seedlings <76 cm tall, but was only 50–60% for seedlings 76 to 137 cm tall (Fig. 1*a*). Sapling mortality was decreased substantially as DBH increased, with only 18% of 7.5 to 10-cm DBH saplings succumbing to fire (Fig. 1*b*). These differences in mortality among the seedling- and sapling-sized trees indicate that the timing of prescribed fire return intervals is important if managers have specific mortality or survival objectives (Battaglia *et al.* 2008).

The significance of ponderosa pine tree size in predicting the probability of fire-induced mortality in seedlings and saplings in our study was not surprising as many studies have reported a decrease in mortality with an increase in large tree diameter (Wyant *et al.* 1986; Harrington 1987, 1993; Saveland and Neuenschwander 1990; Regelbrugge and Conrad 1993; Stephens and Finney 2002; McHugh and Kolb 2003; Keyser *et al.* 2006; Sieg *et al.* 2006). Our results extend these relationships to seedling- and sapling-sized trees. A small tree's size influences the susceptibility of foliage, cambium, and roots to fire damage. In prescribed fires, where flame lengths are often up to 1.5 m tall, seedling foliage is highly susceptible to ignition. Saplings, with live crowns within the maximum range of prescribed flame lengths, are at less risk for crown consumption, but still have foliage highly susceptible to crown scorch. Smaller trees have thinner bark, which influences cambial heat resistance and increases susceptibility to girdling (van Mantgem and Schwartz 2003). A significant amount of fine root biomass is located in the upper 10 cm of the mineral soil (van Haverbeke 1963; Dumm 2003; Smith *et al.* 2004; Hart *et al.* 2005). This increases the susceptibility of seedlings and saplings to root damage during fire and subsequent mortality.

The seedling–flame length mortality model indicated that shorter seedlings are more susceptible to shorter flames, but as flames increase in length, seedling height is less of a factor. For instance, mortality of seedlings less than 60 cm tall was associated with flames less than 5 cm long, but mortality of taller seedlings (107 to 137 cm) required flame lengths of ~45 cm (Fig. 3*a*). On average, observed flame lengths during the Medicine prescribed burn were at least 15 to 30 cm long. These flame lengths resulted in torching fire behavior within the smaller seedling sizes, resulting in high levels of crown scorch and consumption, and subsequently higher mortality rates. However, the lower mortality observed in the taller seedlings and sapling-sized regeneration suggests that a combination of crown damage due to convective heat and other fire-related damage agents (Tables 5 and 6) are required when flame lengths are short. In fact, some taller seedlings and saplings survived after experiencing 100% crown scorch when GC or BC was low (Figs 2*a* and 4). Other studies also note this potential for ponderosa pine to recover from high levels of crown scorch (Wagener 1961; Harrington 1993; Hood *et al.* 2007), which highlights this species' tolerance to surface fire.

The sapling flame length–mortality models predicted flames exceeding 1 m in length were needed to kill sapling-sized ponderosa pine regeneration. On average, flame lengths during the Buffalo burn used to build the model did not exceed 1.4 m, so mortality predictions above that level were extrapolated. However, these extrapolated predictions appear to agree with the sapling mortality observed on the Bullock, Horse Nugget, Lafferty Gulch, and Rankin Tower prescribed burns, where we predicted flame lengths based on bole scorch height (Fig. 5).

Users of the flame length–mortality models should keep in mind that we utilized the average observed flame lengths to develop these models. In general, flame lengths can be quite variable over very small scales (e.g. individual trees) for many reasons. For example, herbaceous fuels and surface woody fuels are often not uniformly distributed and can result in a sudden change in flame length. Wind speed reduction due to increased tree density can reduce expected flame lengths. The presence of ladder fuels can increase flame lengths if the crown base height is low enough to ignite. This variability in flame lengths can therefore impact the predicted probability of mortality and should be taken into account when planning specific flame lengths to meet survival or mortality objectives.

As the sapling live crown reaches heights beyond the reach of direct flames, heat damage to the cambial tissue from flaming and smouldering combustion combined with crown injury became an important predictive variable in the present study, similarly to the results of larger tree diameter studies (Wyant *et al.* 1986; Stephens and Finney 2002; McHugh and Kolb 2003; van Mantgem and Schwartz 2004; Keyser *et al.* 2006; Thies *et al.* 2006; Hood *et al.* 2007). Cambial damage in conjunction with crown damage disrupts photosynthesis and water and nutrient uptake, making it harder for a tree to recover. Our fire-damage models support the hypothesis put forth by van Mantgem and Schwartz (2004) that the additive effect of damage to different tree organs results in tree death.

Measures of GC severity or fuel consumption in conjunction with other damage variables (crown and cambial damage) have been shown to enhance prediction of mortality in ponderosa pine trees >5 cm DBH in some studies (Swezy and Agee 1991; Stephens and Finney 2002; Sieg *et al*. 2006) but not in others (McHugh and Kolb 2003; Thies *et al*. 2006). In both the seedling and sapling mortality models of our study, ground char severity was an important factor in conjunction with other damage variables in predicting mortality (Tables 5 and 6), another supporting fact for the multiple-injury hypothesis. Seedlings in our study with no GC had low predicted mortality, unless a substantial amount of the crown was damaged (Fig. 2*a*). However, as GC severity increased, less crown damage was required to increase mortality levels (Fig. 2*c*, *e*, *g*). Sapling mortality also increased with an increase in GC severity, but it required even greater amounts of crown damage, in the form of crown consumption, to increase the probability of mortality substantially, especially as DBH increased (Fig. 4).

Differences in seedling and sapling response to ground char severity may be a function of biomass allocation to roots. Ground char severity is a surrogate measure of duff consumption and subsequent fine root mortality (Ryan and Noste 1985; Swezy and Agee 1991). Ponderosa pine seedlings allocate over 50% of their biomass to roots whereas saplings only allocate ∼11% (Grunkle and Retzlaff 2001). Most of the fine root biomass is located in the upper 10 cm of the mineral soil (van Haverbeke 1963; Dumm 2003; Smith *et al*. 2004; Hart *et al*. 2005) and it is at this depth that fine-root and associated mycorrhizae biomass significantly decrease after low-intensity prescribed fires (Swezy and Agee 1991; Dumm 2003; Smith *et al*. 2004; Hart *et al*. 2005). The combination of crown damage and some root mortality was enough to impact the seedlings' water and nutrient uptake ability. However, it took greater amounts of GC to impact the saplings (Fig. 4).

We found that GC and BC severity were highly correlated in the sapling observations, but not for the seedlings when GC severity was combined with the other damage variables. This discrepancy in correlation between seedlings and saplings is likely a result of the fuel bed. Seedlings were often found in open gaps within the forest matrix or under low-density overstoreys. These environments typically have a herbaceous fuel bed (Shepperd and Battaglia 2002; Battaglia 2007). In contrast, saplings were found under a gradient of overstorey conditions with fuel beds that ranged from herbaceous fuels to needle litter and woody surface fuels. In areas with a herbaceous fuel bed, fires would move quickly with lower impacts on the surface, shorter flame lengths, and little residual heating from smouldering combustion while still scorching the bole. In contrast, in areas with a needle and woody fuel bed, fires would move more slowly and have an impact on the ground and the bole simultaneously through taller flame lengths and smouldering combustion.

Current mortality models for small- and large-diameter trees used in fire behavior and effects models do not include cambial or GC damage. The inclusion of these variables should be incorporated into mortality models to improve post-fire mortality predictions. Better predictive potential would provide managers with the needed science-based information for planning prescribed burns and post-fire management decisions.

## Conclusions

Sustaining fuel reduction treatments in the Black Hills will require the control of ponderosa pine regeneration densities. Because mechanical thinning of small trees is not economical in the Black Hills, there is interest in using prescribed fire to maintain low regeneration densities. Traditionally, prescribed burn plans are written with the goal of limiting mortality to the regeneration and overstorey. However, control of small trees while limiting mortality of larger trees will be required to maintain fuel treatment effectiveness over time. Fire managers are looking for ways to achieve this goal.

The models developed in the present study will aid managers in the planning of prescribed burns. Our models relate flame length and seedling and sapling height or DBH to mortality, thereby providing managers with benchmark flame lengths needed to kill ponderosa pine seedlings and small-diameter saplings. Incorporating these models into fire behavior and effects software programs, such as *Behave-Plus*, the *Fire and Fuels Extension to the Forest Vegetation Simulator* (*FFE-FVS*), and the *First Order Fire Effects Model* (*FOFEM*), commonly used by managers to evaluate fuel treatment alternatives (Reinhardt *et al*. 1997; Andrews *et al*. 2003; Reinhardt and Crookston 2003) would be useful to managers.

The differences in mortality thresholds for ponderosa pine seedlings and saplings highlight their susceptibility to different damage pathways and give managers several options when designing burn prescriptions. Seedlings are more susceptible to ground and basal char at lower levels of crown damage than saplings. Seedling mortality can therefore be achieved with a fast-moving, low-intensity fire that inflicts elevated damage to the crown, but light damage to the cambium and ground. Alternatively, slow-moving fire that results in moderate levels of crown damage and moderate to high damage to the ground and cambium can achieve the same effect. To achieve sapling mortality, some crown consumption is needed (Fig. 4). This requires flames long enough to climb into the sapling crowns. If tall flame lengths are not possible, then high levels of ground and cambium damage will be needed to compensate for lower levels of crown consumption. This is possible if managers burn under drier conditions to allow larger-diameter (>7.62 cm) fuels to contribute to fire intensity. Alternatively, managers can add more activity fuels to create a more intense fire in order to use fire as a tool to reduce ponderosa pine sapling densities.

Managers face a dilemma when using prescribed fire as a tool to kill ponderosa pine saplings. The amount of damage and associated fire behavior required to successful kill a sapling-sized ponderosa pine can also result in undesirable fire effects for the overstorey trees. There is a danger of the fire being carried into the overstorey canopy and escaping or high cambium damage, both resulting in overstorey mortality. This risk highlights the importance of burning when regeneration is seedling-sized, rather than waiting until sapling-sized trees are present.

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## References

Anderson HE (1982) Aids to determining fuel models for estimating fire behavior. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-122. (Ogden, UT)

Andrews PL, Bevins CD, Seli RC (2003) BehavePlus fire modeling system, version 2.0: user's guide. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-106WWW. (Ogden, UT)

Battaglia MA (2007) Maintaining fuel treatments with prescribed fire in ponderosa pine (*Pinus ponderosa*) forests of the Black Hills, South Dakota. PhD dissertation, Colorado State University, Fort Collins, CO.

Battaglia MA, Smith FW, Shepperd WD (2008) Can prescribed fire be used to maintain fuel treatment effectiveness over time in Black Hills ponderosa pine forests? *Forest Ecology and Management* **256**, 2029–2038. doi:10.1016/J.FORECO.2008.07.026

Brown JK, DeByle NV (1987) Fire damage, mortality, and suckering in aspen. *Canadian Journal of Forest Research* **17**, 1100–1109. doi:10.1139/X87-168

Brown PM (2003) Fire, climate, and forest structure in Black Hills ponderosa pine forests. PhD dissertation, Colorado State University, Fort Collins, CO.

Brown PM, Cook B (2006) Early settlement forest structure in Black Hills ponderosa pine forests. *Forest Ecology and Management* **223**, 284–290. doi:10.1016/J.FORECO.2005.11.008

Brown PM, Sieg CH (1996) Fire history in interior ponderosa pine forests of the Black Hills, South Dakota, USA. *International Journal of Wildland Fire* **6**, 97–105. doi:10.1071/WF9960097

Brown PM, Sieg CH (1999) Historical variability in fire at the ponderosa pine–Northern Great Plains prairie ecotone, south-eastern Black Hills, South Dakota. *Ecoscience* **6**, 539–547.

Brown PM, Ryan MG, Andrews TG (2000) Historical surface fire frequency in ponderosa pine stands in research natural areas, Central Rocky Mountains and Black Hills, USA. *Natural Areas Journal* **20**, 133–139.

Cain MD (1984) Height of stem-bark char underestimates flame length in prescribed burns. *Fire Management Notes* **45**, 17–21.

DeBlander LT (2002) Forest resources of the Black Hills National Forest. USDA Forest Service, Rocky Mountain Research Station. (Ogden, UT)

Driscoll DG, Hamade GR, Kenner SJ (2000) Summary of precipitation data for the Black Hills area of South Dakota, water years 1931–1998. US Geological Survey Open-File Report 00–329. (Rapid City, SD)

Dumm G (2003) Fire effects on fine roots and ectomycorrhizae of ponderosa pine and Douglas-fir following a prescribed burn in a central Idaho forest. MSc thesis, University of Idaho, Moscow, ID.

Fajardo A, Graham JM, Goodburn JM, Fiedler CE (2007) Ten-year responses of ponderosa pine growth, vigor, and recruitment to restoration treatments in the Bitterroot Moutains, Montana, USA. *Forest Ecology and Management* **243**, 50–60. doi:10.1016/J.FORECO.2007.02.006

Frandsen WH, Ryan KC (1986) Soil moisture reduces belowground heat flux and soil temperatures under a burning fuel pile. *Canadian Journal of Forest Research* **16**, 244–248. doi:10.1139/X86-043

Grunkle NE, Retzlaff WA (2001) Changes in physiological attributes of ponderosa pine from seedling to mature tree. *Tree Physiology* **21**, 275–286.

Harrington MG (1987) Ponderosa pine mortality from spring, summer, and fall crown scorching. *Western Journal of Applied Forestry* **2**, 14–16.

Harrington MG (1993) Predicting *Pinus ponderosa* mortality from dormant season and growing season injury. *International Journal of Wildland Fire* **3**, 65–72. doi:10.1071/WF9930065

Hart SC, Classen AT, Wright RJ (2005) Long-term interval burning alters fine root and mycorrhizal dynamics in a ponderosa pine forest. *Journal of Applied Ecology* **42**, 752–761. doi:10.1111/J.1365-2664.2005.01055.X

Hartford RA, Frandsen WH (1992) When it's hot, it's hot. . . or maybe it's not! (surface flaming may not portend extensive soil heating). *International Journal of Wildland Fire* **2**, 139–144. doi:10.1071/WF9920139

Hood S, Bentz B (2007) Predicting post-fire Douglas-fir beetle attacks and tree mortality in the Northern Rocky Mountains. *Canadian Journal of Forest Research* **37**, 1058–1069. doi:10.1139/X06-313

Hood SM, McHugh CW, Ryan KC, Reinhardt E, Smith SL (2007) Evaluation of a post-fire tree mortality model for western USA conifers. *International Journal of Wildland Fire* **16**, 679–689. doi:10.1071/WF06122

Hosmer D, Lemeshow S (2000) 'Applied Logistic Regression.' (Wiley: New York)

Keyser TL, Smith FW, Lentile LB, Shepperd WD (2006) Modeling post-fire mortality of ponderosa pine following a mixed-severity wildfire in the Black Hills: the role of tree morphology and direct fire effects. *Forest Science* **52**, 530–539.

Kobziar L, Moghaddas J, Stephens SL (2006) Tree mortality patterns following prescribed fires in a mixed conifer forest. *Canadian Journal of Forest Research* **36**, 3222–3238. doi:10.1139/X06-183

Lynch DW (1959) Effects of wildfire on mortality and growth of young ponderosa pine trees. USDA Forest Service Research Note, INT-66. (Ogden, UT)

Morris WG, Mowat EL (1958) Some effects of thinning a ponderosa pine thicket with a prescribed fire. *Journal of Forestry* **56**, 203–209.

McHugh CW, Kolb TE (2003) Ponderosa pine mortality following fire in northern Arizona. *International Journal of Wildland Fire* **12**, 7–22. doi:10.1071/WF02054

Oliver WW, Ryker RA (1990) *Pinus ponderosa* Dougl. ex Laws. Ponderosa pine. In 'Silvics of North America', Agriculture Handbook 654. (Eds RM Burns, BH Honkola) pp. 173–180. (USDA Forest Service: Washington, DC)

Peterson DL (1985) Crown scorch volume and scorch height: estimates of post-fire tree condition. *Canadian Journal of Forest Research* **15**, 596–598.

Peterson DL, Arbaugh MJ (1986) Post-fire survival of Douglas-fir and lodgepole pine: comparing the effects of crown and bole damage. *Canadian Journal of Forest Research* **16**, 1175–1179. doi:10.1139/X86-209

Peterson DL, Arbaugh MJ (1989) Estimating post-fire survival of Douglas-fir in the Cascade Range. *Canadian Journal of Forest Research* **19**, 530–533. doi:10.1139/X89-084

Regelbrugge JC, Conrad SG (1993) Modeling tree mortality following wildfire in *Pinus ponderosa* forests in the central Sierra Nevada of California. *International Journal of Wildland Fire* **3**, 139–148. doi:10.1071/WF9930139

Reinhardt E, Crookston N (2003) The Fire and Fuels Extension to the Forest Vegetation Simulator. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-116. (Ogden, UT)

Reinhardt ED, Keane RE, Brown JK (1997) First Order Fire Effects Model: FOFEM 4.0. User's guide. USDA Forest Service, Intermountain Research Station, General Technical Report INT-GTR-344. (Ogden, UT)

Ryan KC (1982) Techniques for assessing fire damage to trees. In 'Proceedings of the Symposium: Fire – its Field Effects', 19–21 October 1982, Jackson, WY. (Ed. JE Lotan) pp. 2–10. (Intermountain Fire Council: Missoula, MT)

Ryan KC, Noste NV (1985) Evaluating prescribed fires. In 'Proceedings of the Symposium and Workshop on Wilderness Fire', 15–18 November 1983, Missoula, MT. (Tech. Coords JE Lotan, BM Kilgore, WC Fischer, RW Mutch) USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-82. (Ogden, UT)

Ryan KC, Reinhardt ED (1988) Predicting post-fire mortality of seven western conifers. *Canadian Journal of Forest Research* **18**, 1291–1297. doi:10.1139/X88-199

Ryan KC, Frandsen WD (1991) Basal injury from smouldering fires in mature *Pinus ponderosa* Laws. *International Journal of Wildland Fire* **1**, 107–118. doi:10.1071/WF9910107

Ryan KC, Peterson DL, Reinhardt ED (1988) Modeling long-term fire caused mortality of Douglas-fir. *Forest Science* **34**, 190–199.

SAS Institute (2001) '*SAS/STAT* Software, Version 9.1 of the SAS System for Windows 2000.' (SAS Institute Inc.: Cary, NC)

Saveland JM, Neuenschwander LF (1990) A signal detection framework to evaluate models of tree mortality following fire damage. *Forest Science* **36**, 66–76.

Shepperd WD, Battaglia MA (2002) Ecology, silviculture, and management of Black Hills ponderosa pine. USDA Forest Service, Rocky Mountain Research Station, General Technical Report, RMRS-GTR-97. (Fort Collins, CO)

Sieg CH, McMillin JD, Fowler JF, Allen KK, Negron JF, Wadleigh LL, Anhold JA, Gibson KE (2006) Best predictors for post-fire mortality of ponderosa pine trees in the Intermountain West. *Forest Science* **52**, 718–728.

Smith JE, McKay D, Niwa CG, Thies WG, Brenner G, Spatafora JW (2004) Short-term effects of seasonal prescribed burning on the ectomycorrhizal fungal community and fine root biomass in ponderosa pine stands in the Blue Mountains of Oregon. *Canadian Journal of Forest Research* **34**, 2477–2491. doi:10.1139/X04-124

Stephens SL, Finney MA (2002) Prescribed fire mortality of Sierra Nevada mixed conifer tree species: effects of crown damage and forest floor combustion. *Forest Ecology and Management* **162**, 261–271. doi:10.1016/S0378-1127(01)00521-7

Swezy MD, Agee JK (1991) Prescribed-fire effects on fine-root and tree mortality in old-growth ponderosa pine. *Canadian Journal of Forest Research* **21**, 626–634. doi:10.1139/X91-086

Thies WG, Westling DJ, Loewen M, Brenner G (2006) Prediction of delayed mortality of fire-damaged ponderosa pine following prescribed fires in eastern Oregon, USA. *International Journal of Wildland Fire* **15**, 19–29. doi:10.1071/WF05025

van Haverbeke DF (1963) Root development of ponderosa pine seedlings in the Black Hills. *Ecology* **44**, 161–165. doi:10.2307/1933193

van Mantgem P, Schwartz M (2003) Bark heat resistance of small trees in Californian mixed conifer forests: testing some model assumptions. *Forest Ecology and Management* **178**, 341–352. doi:10.1016/S0378-1127(02)00554-6

van Mantgem P, Schwartz M (2004) An experimental demonstration of stem damage as a predictor of fire-caused mortality for ponderosa pine. *Canadian Journal of Forest Research* **34**, 1343–1347. doi:10.1139/X04-001

van Wagtendonk JW (1983) Prescribed fire effects on forest understory mortality. In 'Seventh Conference on Forest Fire and Meteorology', 25–28 April 1983, Fort Collins, CO. pp. 136–138. (American Meteorological Society: Boston, MA)

Waldrop TA, Lloyd FT (1988) Precommercial thinning a sapling-sized loblolly pine stand with fire. *Southern Journal of Applied Forestry* **12**, 203–207.

Wagener WW (1961) Guidelines for estimating the survival of fire-damaged trees in California. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Miscellaneous Paper 60. (Berkeley, CA)

Wienk CL, Sieg CH, McPherson G (2004) Evaluating the role of cutting treatments, fire and soil seed banks in an experimental framework in ponderosa pine forests of the Black Hills, South Dakota. *Forest Ecology and Management* **192**, 375–393. doi:10.1016/J.FORECO.2004.02.004

Wyant JG, Omi PN, Laven RD (1986) Fire-induced tree mortality in a Colorado ponderosa pine/Douglas-fir stand. *Forest Science* **32**, 49–59.

Wooldridge DD, Weaver H (1965) Some effects of thinning a ponderosa pine thicket with a prescribed fire, II. *Journal of Forestry* **63**, 92–95.

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