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Predicting *Pinus ponderosa* Mortality from Dormant Season and Growing Season Fire Injury

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Abstract. Understory prescribed burning was conducted in an immature *Pinus ponderosa* (ponderosa pine) stand in southwestern Colorado during three seasons, late spring, midsummer, and autumn. Tree mortality from various levels of crown scorch was compared for the different seasons of injury. A total of 526 trees of different sizes, with crown scorch ranging from 20 to 100%, were monitored annually for 10 years.

Over 80% of the 10-year mortality from injury in all three seasons had occurred by year 3, with over 90% occurring by year 4. Mortality of trees scorched in the spring and summer was about 2.5 times greater than that in the autumn for similar crown damage. Most trees larger than 18 cm in diameter survived autumn injury, even with greater than 90% scorching. Following spring and summer injury, trees smaller than 10 cm in diameter died readily with greater than 50% scorching, but about 90% crown scorch was required by large trees to be lethal.

A logistic regression model was developed to predict the probability of mortality given tree size, scorch class, and season of injury. Because mortality was similar within scorch classes less than 90%, they were combined into a single class. Scorch thresholds with large increases in mortality occurred at 90% and 100% crown scorch. The season variable includes two groups, dormant (autumn) and growing (spring and summer). Use of this model to predict mortality of immature *P. ponderosa* is appropriate where stand, fuel, and fire conditions resemble those of this study.

Keywords: Fire effects; Crown scorch; *Pinus ponderosa*; Colorado; Mortality prediction model.

Introduction

Fire is important in many forest types for maintaining forest health, relieving fuel hazards, preparing seedbeds, and manipulating understory vegetation. However, actual fire application lags behind this recognition because of the lack of directly usable fire effects knowledge, an apparent narrow range of acceptable burning conditions, and concern about control problems.

Much prescribed burning is conducted when fuel flammability is relatively low, lessening concerns about control problems and undesirable fire effects. This generally occurs when fuel and weather conditions are relatively cool and damp, most likely in the late autumn or early spring. However, fire application during these "safe" periods often fails to achieve management objectives. For example, burning in the spring may be unsuccessful if reduction of shrubby competitors is desired (Harrington 1985), or a damp autumn burn may consume little duff and expose insufficient mineral soil for conifer seedling establishment (Artley et al. 1978). In addition, smoke from prescribed burns is more likely to add to air pollution problems during autumn when stable air and inversions are most common. For these reasons it is best not to rely on a single burning season simply for safety or convenience.

Resource managers will have more opportunities to achieve their goals if they understand potential fire effects in several burning seasons. For example, knowledge of the impacts of overstory fire injury sustained during different seasons could assist in planning prescribed understory burns.

Few studies have compared overstory mortality from fire injury suffered during different seasons. Ryan et al. (1988) analyzed several independent variables to determine the best predictor of *Pseudotsuga menziesii* (Douglas-fir) mortality. They found that with similar fire injury, trees damaged in the autumn had a greater probability of dying than those damaged in the spring. Season was not considered as important for prediction as tree size and extent of cambial injury. Ferguson (1955) compared the impacts of summer and winter wildfire damage to *Pinus palustris* (longleaf pine), *Pinus echinata* (shortleaf pine), and *Pinus taeda* (loblolly pine). Given similar injury, trees were less likely to survive summer fires. Wagener (1961) developed guidelines for estimating the survival of fire-damaged *Pinus ponderosa* (ponderosa pine) and *Pinus jeffreyi* (Jeffrey pine) in California. He estimated that trees injured before July need at least 35% green foliage remaining to survive. However, they could survive injury in July with just 15 to 25% green foliage, and trees damaged after August 1 should live with at least 10% green foliage if 50% of the crown is alive. Season of fire damage is clearly important.

The main indicators of tree mortality following fire injury are crown damage, cambial death, root mortality, insect attack, tree size and vigor, and post-injury climate (Dieterich 1979; Peterson and Arbaugh 1986; Ryan 1990). Tree size and some measure of crown damage are the most commonly used indicators of the probability of tree mortality because they are physiologically important and highly visible.

Most research that has attempted to quantify and explain conditions that lead to *P. ponderosa* mortality from fire injury has dealt with either effects of growing season (physiologically active) wildfires or dormant season (physiologically inactive) prescribed fires. Therefore, conclusions concerning different responses due to season of injury may be speculative because similar sites have not been contrasted seasonally, and because different types of fires (wildfires vs. prescribed fires) are generally associated with different seasons.

The objectives of this research were to determine the long-term difference in *P. ponderosa* mortality from crown scorch resulting from spring, summer, and autumn prescribed burns, and to develop a model for predicting the probability of mortality, with season of injury as an independent variable.

Methods

The study site is within the San Juan National Forest in southwestern Colorado, U.S.A., at 2,300 m elevation in a *P. ponderosa* stand averaging 740 trees ha^{-1}. A majority of the trees became established in the early 1900's and were mostly 13- to 25-cm diameter at breast height (dbh) when the research began in 1977. A small percentage of the stand is composed of seedlings, saplings, and trees larger than 40 cm dbh The gentle, sloping terrain (less than 5%) has a southwest exposure.

Eighteen, 1-hectare experimental units were established and separated by 1-m wide firelines within a 40-ha stand. Six units were randomly chosen for burning treatments during each of three seasons. Autumn burns were conducted in late October 1977 when the trees were assummed to be entering dormancy because of cool air and soil temperatures, completed bud set, and short day length. Spring burns took place in early June 1978 shortly after bud break when new needles were less than 5 cm long. Summer burning was conducted in mid-August 1978 during the typical rainy season. The three seasonal burn treatments were conducted primarily to determine their respective impacts on the dense *Quercus gambelii* (Gambel oak) understory (Harrington 1985).

Most environmental and fire conditions were similar during the three seasons when the burns were conducted. Air temperature averaged 16°C in the autumn and about 20 to 24°C in the spring and summer. Wind speeds averaged 1.5 m s^{-1} in all burns. Surface fine fuel moisture ranged from 5.5% in the spring to 7.2% in the autumn. Rates of fire spread averaged 2 m min^{-1} in the autumn and summer burns, and up to 2.5 m min^{-1} in the spring burn. Mean flame lengths were about 1 m in all burns.

Overstory fire injury was evaluated several weeks after the burns. In each of 18 experimental units, an attempt was made to locate and tag two trees in each of 20 size class/scorch class categories. The dbh size-class midpoints were 7.5, 15.0, 22.5, and 30.0 cm. Crown scorch was defined as the percentage of live crown length in which foliage was killed, and designated into five scorch classes: 20 to 33%, 34 to 66%, 67 to 89%, 90 to 99%, and 100%. The range of crown scorch was not selected evenly within these classes so the class midpoints were determined to be 30%, 50%, 70%, 90%, and 100%. Trees can be mortally wounded with cambial injury as indicated by moderate to severe bole charring, but this injury was not commonly found because of the nature of the fuels and fires. Therefore, cambial injury was not a factor in this study. The number of trees tagged for observation was 180, 162, and 184 in the autumn, spring, and summer burn treatments, respectively.

Analyses

Two-factor analysis of variance procedures were conducted to determine if mortality differences were indicated within the dbh classes and within the crown scorch classes by season.

Logistic regression models are frequently used to predict the probabilities of binary results (that is, live or dead) given independent information. Monserud (1976) contrasts this modeling form to other prediction functions. Logistic regression has often been used to predict tree mortality or survivability given various fire damage classifications and tree characteristics (Bevins

1980; Harrington and Hawksworth 1990; Saveland et al. 1990).

Three independent variables were tested in developing a logistic regression model in this study: tree dbh class, crown scorch class, and season of fire injury. Tree dbh class is a quantitative variable because the values are actual diameters and class intervals are equal. Even though the crown scorch class represents actual scorch percentages, it must be classified as a qualitative variable because class intervals are not equal (Hosmer and Lemeshow 1989). Because season is not quantifiable, it is also a qualitative variable. The dependent variable for each tree is a vitality class, either dead or alive. The model predicts the probability of tree mortality given a specific set of independent variables.

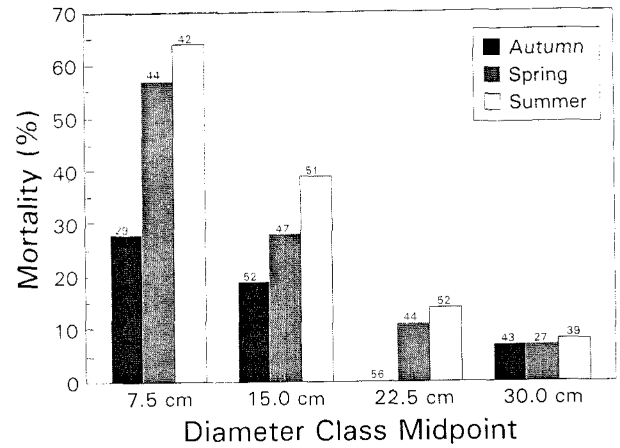

Figure 2. Comparative 10-year mortality in four diameter classes of *Pinus ponderosa* following crown scorch in spring, summer, or autumn. Numbers above bars indicate sample sizes.

Results

Ten years after the prescribed burns, 12% of the trees scorched in the autumn had died, compared to 28% in the spring treatment and 30% in the summer treatment. In all, 123 (23%) of the 526 tagged trees died. Sixty percent of the 10-year mortality had occurred after the first year and about 90% had occurred by the end of year 4 (Fig. 1). No trees in the autumn fire treatment died after year 5. After the first year, mortality from autumn injury was just 25% of that from spring and summer injury. During the next 3 years, mortality from autumn damage was 33 to 67% of that from spring and summer damage.

Figure 2 points out that the greatest tree death followed spring and summer injury in all size classes except the 30.0-cm dbh class in which mortality was equally low for all seasons. The resilience of the 22.5-cm dbh class is worth noting as none of the 56 trees in the autumn burn died, even though 20 had more than 90% crown scorch. As expected, mortality decreased with increasing tree size.

The three lowest crown scorch levels resulted in distinctly less total mortality and slower mortality rates than the two highest levels regardless of season or dbh (Fig. 3). Early mortality for trees in the 30% class was somewhat less than for trees in the 50% and 70% classes, but, with the exception of year 4, rates were similar thereafter. Mortality totals and rates for 100% scorched trees were substantially greater in the first few years than those scorched 90%. None of the trees with complete crown scorch died after year 5; however, all but one of the survivors had been injured in the autumn.

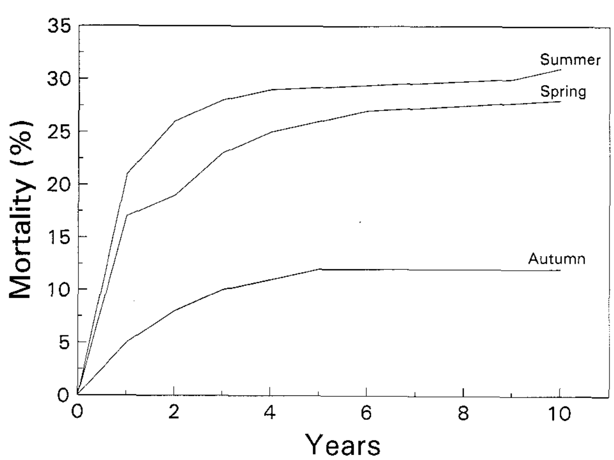

Figure 1. Cumulative 10-year mortality of *Pinus ponderosa* scorched in spring, summer, or autumn prescribed fires. Sample sizes are spring = 162, summer = 184, and autumn = 180 trees.

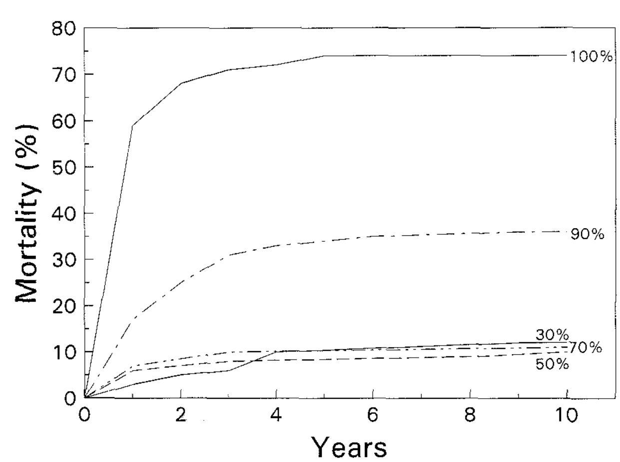

Figure 3. Cumulative 10-year mortality of *Pinus ponderosa* in five crown scorch classes. Sample sizes for scorch classes are 30% = 125, 50% = 121, 70% = 106, 90% = 106, and 100% = 68.

Table 1 compares average dbh and average crown scorch of live and dead trees by season of injury. Trees living 10 years after injury averaged about 7 cm larger at the time of injury than trees that died, indicating that small trees succumb to fire damage more readily than larger trees. In addition, dead trees had significantly greater crown scorch than survivors within each season. Significant size differences among seasons were not found within live and dead categories. However, trees that survived autumn injury had a significantly greater amount of crown scorch than trees that survived spring and summer injury, indicating that dormant trees can survive greater damage than actively growing trees. In general, mortality increased with decreasing tree size, with increasing crown scorch, and with injuries that occurred during a period of greater physiological activity (spring and summer).

Several multiple logistic regressions were produced to predict mortality. Different combinations of dbh classes, scorch classes, and seasons were tested to produce the statistically best and most biologically realistic regression. When each independent variable was used separately, mortality probabilities were found to be similar among several categories for each variable. Figure 1 shows the uniformity of mortality from spring and summer fire injury. Figure 3 shows nearly equal mortality among scorch classes 30%, 50%, and 70%. Therefore, to develop a simple, logical regression, similar categories were combined, yielding the following independent variable classes: season - dormant (autumn) and growing (spring and summer); scorch classes - 50% (30%, 50%, and 70%), 90%, and 100%. Also, diameter class midpoints were used, not actual diameters.

The simplest and most logical regression is as follows:

$$P_m = 1/(1 + e^{(-1.16 + 1.04S + 1.94L + 0.12H + 0.14D)}) \qquad (1)$$

where P_m = probability of mortality
e = base of natural log
S = season (dormant: S = 1; growing: S = -1)
L = low scorch
H = high scorch
(50% scorch: L = 1 and H = 0; 90% scorch: L = 0 H = 1; 100% scorch: L = -1 and H = -1)
D = diameter class (7.5, 15.0, 22.5, or 30.0 cm)

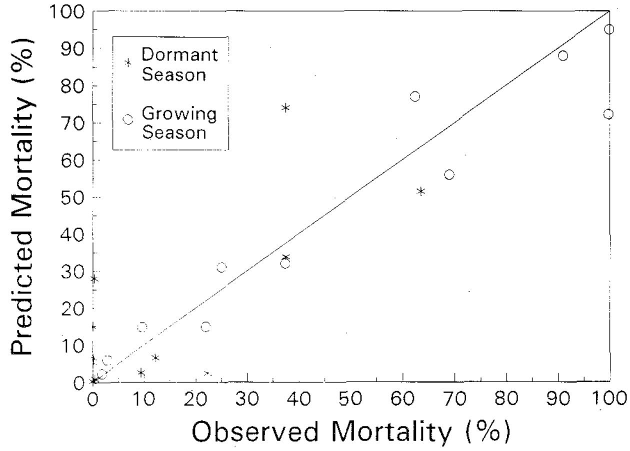

Figure 4. A comparison of predicted mortality from Equation 1 and observed mortality for *Pinus ponderosa* with dormant and growing season crown scorch. The line of exact agreement is shown.

All coefficients were significantly different from zero ($p < 0.01$). However, the goodness of fit test for the regression model indicates that the observed and predicted values are significantly different. This significance appears to be due primarily to differences within two size/scorch categories. In the dormant season, 72% of 7.5-cm dbh trees with 100% scorch are predicted to die, but only 38% actually did, and 24% of 22.5-cm dbh trees with 100% scorch are predicted to die, but all survived.

A plot of observed vs. predicted probability of mortality is shown in Figure 4. Mortality prediction for growing season fire injury is better than for the dormant season. This is because the model predicted some mortality in several of the dbh/scorch categories in the dormant season in which no mortality occurred. Using the 50% probability of mortality level to segregate live and dead trees, the model correctly predicted vitality for 87% of the trees. Nine percent of the trees died when predicted to live and 4% of the trees lived when predicted to die.

Because season, scorch, and dbh have only a few values each, the prediction regression can be used most simply by referring to Table 2. The table shows estimated probabilities of mortality for all combinations of independent variables encountered in this

Table 1. Mean diameters and crown scorch for live and dead *Pinus ponderosa* damaged during spring, summer, or autumn prescribed fires.

	Live			Dead		
	Autumn	Spring	Summer	Autumn	Spring	Summer
DBH (cm)	20.8a*	19.8a	21.6a	14.5b	12.7b	13.2b
Crown Scorch (%)	63.9a	52.5b	56.0b	82.9c	83.6c	83.3c

*Means within dbh or crown scorch rows followed by different letters are significantly different ($p < 0.05$).

Table 2. The estimated probability of mortality (%) for *Pinus ponderosa* in four dbh classes, three crown scorch classes, and two seasons. Values are from Equation 1.

		DBH			
		7.5 cm (3.8 - 11.3 cm)	15.0 cm (11.4 - 18.7 cm)	22.5 cm (18.8 - 26.3 cm)	30.0 cm (26.4 - 33.8 cm)
Season	Scorch (%)	%			
Dormant	50	3	2	1	1
	90	31	14	6	2
	100	71	47	24	10
Growing	50	32	14	6	2
	90	79	57	32	14
	100	95	88	72	48

study. The tabular values can be considered either the percentage of trees with specific characteristics that will die, or the probability that a specific tree with these characteristics will die.

Discussion

Several general results verify previous research. First, mortality increased with decreasing tree size as reported by Davis et al. (1968), Potter and Foxx (1979), and Wyant et al. (1986). This happens not only because crowns of smaller trees are closer to the fire and sustain greater injury but also because these trees are frequently in a low vigor, suppressed state with little tolerance for damage. Second, mortality generally increased with increasing crown scorch as reported by Lynch (1959), Harrington and Hawksworth (1990), and Saveland et al. (1990).

Several studies relating crown scorch to *P. ponderosa* mortality show a scorching threshold beyond which mortality increases dramatically. In this study, mortality was quite similar for scorch classes of 30 to 70%. Mortality increased substantially in both the dormant and growing seasons between the 70% and 90% classes, and again between the 90% and 100% classes (Fig. 3). Lynch (1959) showed that *P. ponderosa* mortality following a July wildfire was less than 25% with up to about 75% crown scorch. With about 85% crown scorch, mortality increased dramatically. All trees died with greater than 90% crown scorch. Potter and Foxx (1979) reported less than 10% *P. ponderosa* mortality with under 75% crown damage from a June wildfire and 20% mortality in the 76 to 90% scorch class. Ninety-four percent of their trees died following 100% crown scorch. Herman (1954) found *P. ponderosa* mortality thresholds at about 50% scorching, with little survival above 70% scorch. In his study, most trees with greater than 60% crown scorch also had severe bole charring implying cambium injury. Therefore, when bole charring is minimal, other research which relates *P. ponderosa* mortality to crown scorch compares favorably to the results of this study. Mortality from growing season fires appears to be low to moderate until crown damage exceeds 70 to 75%.

These apparent scorching thresholds could be related to differences in photosynthetic efficiency among crown strata. Helms' (1970) research indicates that photosynthate production per unit area of 1-year-old needles in the mid- and lower crowns of *P. ponderosa* was only about 70% and 50%, respectively, of that in the upper crowns. Therefore, photosynthate production should remain relatively high and transpiration should be reduced with the loss of the lower crown (Wyant 1981). Furthermore, the highest efficiency foliage would still be active even with 70 to 75% crown scorch. With this level of crown loss, a tree apparently would have a high potential to produce enough photosynthate for survival, but not enough for normal height and diameter growth. Once scorch levels approach 90%, a large percentage of the most productive foliage would be lost, so a sudden drop in survival would be expected. Another threshold would be reached with 100% crown scorch where no survival would be expected after growing season injury. However, up to 20% of the buds may survive 100% scorching during the dormant season (Ryan 1990). The high photosynthate production of this upper crown foliage apparently allowed relatively high survival.

Dormant season fire damage resulted in minimal mortality in all cases except small trees with 100% crown scorch. In this study area, trees greater than 18 cm dbh appeared to be quite resilient and healthy as only 3 of 27 with over 90% scorching eventually died. Dieterich (1979) monitored *P. ponderosa* mortality following a dormant season wildfire. All trees in his sample had greater than 75% crown scorch and were in similar immature size classes as the current study. Approximately one-fourth of the trees died, but two-thirds of these had experienced some crown consumption, indicating a more intense fire than in the current study. Dieterich (1979) concluded that without crown consumption the probability of survival is high when crown scorch is less than 90%, which conservatively agrees with the results of this study.

Moisture stress from deficient precipitation was an unlikely factor in the results of this study. During the 10 postburn years, annual precipitation ranged from 85 to 140% of average.

Other research has yielded regressions for estimating the probability of mortality for western conifers. Ryan and Reinhardt (1988) developed a model for estimating mortality of seven western conifers damaged in prescribed fires. Even though this model did not use *P. ponderosa* data, it has a bark thickness variable that separates the responses of different species to fire injury. Keane et al. (1990) used this equation to predict both *P. ponderosa* and *P. menziesii* mortality in a successional process model. The equation predicts greater than 50% probability of *P. ponderosa* mortality with 50% or more crown scorch on 22.5-cm d.b.h trees and a similar probability with less than 20% crown scorch on 7.5-cm dbh trees. The model overpredicts mortality compared to that observed in this study. The inconsistency may be due to the absence of fire-damaged *P. ponderosa* in the development of the Ryan and Reinhardt (1988) model.

Two mortality prediction models have been generated specifically for *P. ponderosa*. Saveland et al. (1990) modeled mortality following autumn prescribed burns in northern Idaho. That model could not be compared with the model produced in this study because scorch height is the primary damage variable. The other model, which also predicts mortality from a autumn prescribed burn, uses tree dbh and percent crown scorch as independent variables (Wyant 1981), allowing a direct comparison with Eq. 1 of this study. With about 65% crown scorch of 22.5-cm dbh trees, Wyant (1981) predicts greater than 50% probability of mortality compared to less than 5% mortality predicted from this study. Also, with about 54% crown scorch of 7.5-cm dbh trees, Wyant (1981) predicts greater than 50% probability of mortality compared to about 10% predicted from this study. Differences in the two predictions could be partially due to greater bole damage in Wyant's study.

The results reported here are unique in that a season variable is included. Seasonal mortality differences were quite evident and are probably due to contrasts in physiological activity and carbohydrate storage. Physiological activity was greatly reduced at the time of the autumn burns in response to short day lengths and cool air and soil temperatures (Fritts 1976, Kozlowski et al. 1991). Most tree growth had presumably ceased and reserve carbohydrates had been at least partially replenished by this time (Kramer and Kozlowski 1979). These carbohydrate reserves should have allowed the normal early season root and shoot growth that occurs before large quantities of photosynthate are available. In addition, many dormant, protected buds likely survived within scorched crowns, producing new foliage the following spring (Ryan 1990).

Of interest were the similar responses of trees damaged in late spring and midsummer and their collective difference from those damaged in the autumn. A high level of physiological activity is apparently maintained throughout the late spring and summer to the extent that a negative response to injury is high. In mid- to late-spring this activity includes bud break and growth of new foliage, cones, and roots (Fritts 1976, Schubert 1974). Because bud break had taken place at the time of the spring burns, both new and old foliage were scorched, resulting in greater crown damage than that from autumn injury with equal visible scorching. Substantial reductions in leaf area depress photosynthesis, and yet respiration for general maintenance, growth, and production of chemical defenses continues (Ryan 1990). A reduced photosynthesis-to-respiration ratio can lead to carbon, moisture, and nutritional imbalances and to increased probability of mortality (Chambers et al. 1986). Diameter growth and completion of bud formation, in addition to root growth, are likely occurring in August in response to increases in available soil moisture from summer rains (Schubert 1974). High scorching during the summer leaves less foliage for photosynthate production for these functions. Also, because depleted carboydrates are replenished during the late summer, any crown loss reduces carbohydrate storage, affecting root and shoot growth the following spring (Kramer and Koslowski 1979). Extended rainless periods are a regular feature of the southwestern *P. ponderosa* zone, occurring in late spring and early autumn. Spring root production is likely important here, as in other regions (Grier 1989), to minimize moisture stress. Therefore, reduced photosynthate production and carbohydrate storage following growing season crown injury could result in moisture stress because of depressed root growth.

In summary, a logistic regression is presented that predicts the probability of mortality for immature *P. ponderosa* sustaining various levels of crown scorch during two physiologically distinct seasons. The quantified damage resulted from prescribed underburns with intensities high enough to cause complete crown scorch but with fuel consumption low enough to cause only minimal cambial injury. This model should be applicable for predicting mortality probabilities in young *P. ponderosa* stands with fuel and fire conditions resembling those found in this study. Variations from the predictions made by this model could result from severe insect attacks on fire-damaged trees, unusual drought conditions for several years after injury, or injury to stressed, low vigor trees.

The seasonal aspect of fire application has not been thoroughly addressed in previous tree mortality research. However, it appears to be an important issue as managers consider the value of fire for more ecologically sound vegetation management and as they seek ways to ameliorate the growing problem of smoke emissions.

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