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Prescribed fire mortality of Sierra Nevada mixed conifer tree species: effects of crown damage and forest floor combustion

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Abstract

Logistic regression equations of prescribed fire mortality were developed for white fir (*Abies concolor* [Gord. and Glend.] Lindl.), sugar pine (*Pinus lambertiana* Dougl.), ponderosa pine (*Pinus ponderosa* Laws.), incense-cedar (*Calocedrus decurrens* [Torr.] Floren.), and giant sequoia (*Sequoiadendron giganteum* [Lindley] Buchholz) in the southern Sierra Nevada, California. A total of 1025 trees were analyzed in this study. Variables included in the mortality equations are diameter at breast height, percent crown volume scorched, crown scorch height, and local forest floor consumption. The likelihood ratio χ^2 was highly significant ($P < 0.0001$) for all models developed and the receiver operating curve statistic ranged from 0.736 to 0.997 indicating good overall model performance. None of the logistic regression models developed for California black oak (*Quercus kelloggii* Newb.) produced a maximum likelihood estimate indicating that the variables measured were not significant predictors of mortality. Probability of death is lower for giant sequoia, incense-cedar, and ponderosa pine at high levels of percent crown volume scorched when compared to sugar pine and white fir. Forest floor consumption was a significant factor in the majority of the models developed indicating that mortality is not solely a function of crown damage. These models may be useful to forest managers planning prescribed fires and to ecologists interested in modeling the effects of fire on mixed conifer forests.

Keywords: Logistic regression; Giant sequoia; Mortality models; Fuel loads; Fire effects; California black oak

1. Introduction

The use of prescribed fire in forest restoration is forecast to sharply increase in the next decade (USDA, 1995). Many of these fires will be designed to reduce the density of small to moderately sized trees since these structures increase the probability of extreme fire behavior (van Wagtendonk, 1996; Stephens, 1998).

In the western United States, fire-caused tree mortality has been modeled using the amount of crown scorched or consumed as independent variables (Lynch, 1959; Dieterich, 1979; Mitchell and Martin, 1980; Bevins, 1980; Wyant et al., 1986). Other factors such as bark char height have been used in conjunction with crown damage to predict tree mortality (Peterson and Arbaugh, 1986, 1989). In the inland

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Pacific Northwest, mortality of seven tree species was modeled using logistic regression analysis (Ryan and Reinhardt, 1988). Independent variables included bark thickness and percentage of the crown killed, resistance to cambium injury was assumed to vary with bark thickness. Probability of death increased with percentage of crown killed and decreased as bark thickness increased. Bark thickness is an important characteristic because it can reduce or prevent cambium injury (Martin, 1963).

Few models have used fire characteristics to predict tree mortality. In the Sierra Nevada, flame length has been used to model mortality of small mixed conifer trees (van Wagtendonk, 1983). Other models have also been developed that correlate cambium injury with fuel consumption variables in mechanically thinned conifer stands (Ryan and Steele, 1990).

Logistic regression analysis has also been used to model mortality after wildfire. Ponderosa pine (*Pinus ponderosa* Laws.) mortality 2 years after the 1987 Stanislaus complex fires was modeled using logistic regression (Regelbrugge and Conard, 1993). Independent variables used were diameter at breast height (DBH) and height of bark char. A second model was developed using relative char height (height of stem-bark char as a proportion of tree height). Probability of mortality increased with increasing height of stem-bark char and scorch height, and decreased with increased DBH. From the available literature, the best indicator of crown injury appears to be the proportion of the crown scorched or killed (Ryan, 1982; Peterson, 1985; Ryan et al., 1988).

1.1. *Effects of fire*

The physical effects of fire on trees depend on the characteristics of both the trees and the fires (Ryan, 1990). The extent of damage to leaves, buds, stems, cambium, and fine roots largely determines the likelihood of death. Damage to living tissues depends on the duration of elevated temperature from both flaming and smoldering combustion. A temperature of 60 °C for 1 min is considered lethal for plant tissues (Hare, 1961). Larger trees are more resistant to fire damage because of thicker bark, higher position of the foliage, and the increase in heat sink capacity with an increase in tree mass (Martin, 1963; Costa et al., 1991).

Higher surface fuel and forest floor consumption is expected to increase tree mortality because it directly affects the duration and amount of heating of the tree stem and roots (Ryan, 1982). Forest fuels that consist of larger dead woody fuels and deep litter and duff layers release only a fraction of their energy in the flaming front. The majority of energy released in these types of forests is by smoldering and intermittent combustion after the flaming front has passed (Kauffman and Martin, 1989).

Heating of the soil or tree bole may be unrelated to flame characteristics (Hartford and Frandsen, 1992). Duff consumption proceeds almost entirely by slow smoldering combustion according to its moisture and inorganic content (Frandsen, 1987, 1991). Consumption of duff and woody fuels is strongly dependent on moisture content (Sandberg, 1980; Brown et al., 1985; Reinhardt et al., 1991) and in some cases, combustion of high surface fuel loads will increase duff and litter consumption (Little et al., 1986; Albini and Reinhardt, 1995). Furthermore, the duff layer in natural stands often constitutes the largest single fuel fraction and is the most uniform of all components of the surface and ground fuels (Finney and Martin, 1992) but is neglected in most fire mortality studies.

Tree mortality studies that include tree diameter or bark thickness indirectly reflect damages or resistance to injury from such prolonged heating (Ryan and Reinhardt, 1988; Peterson and Ryan, 1986; Wyant et al., 1986). Surface fuel consumption has also been directly related to tree injury (Ryan and Frandsen, 1991; Ryan and Steele, 1990) and root damage (Swezy and Agee, 1991). Root injury is controlled by the spatial distribution of roots, the duration of heating that occurs during combustion, and by the thermal properties of the soil (Hungerford et al., 1991).

The amount of scorch that a tree can withstand may vary by species, size, fuel consumption, and season of burn. Some species such as ponderosa pine can withstand complete crown scorch because large buds can be shielded from lethal temperatures (Dieterich, 1979; Ryan, 1990) whereas other species are killed with moderate levels of crown scorch.

Most mortality models developed for mixed conifer and ponderosa pine forests have used variables that characterize above-ground damage from fire (scorch height, bark char height, percent crown volume scorched). These variables are related to flaming combustion and fireline intensity. Tree mortality may also be influenced by cambial and fine root damage that is produced by during smoldering combustion but no studies have investigated this in the Sierra Nevada. There has also been no research on the prescribed fire mortality of giant sequoia (*Sequoiadendron giganteum* [Lindley] Buchholz).

The objectives of this paper are to develop models of fire-related mortality for the six dominant mixed conifer trees species of the southern Sierra Nevada. Independent variables that characterize both above-ground fire injury and local fuel consumption will be analyzed to determine if each is a significant predictor of mortality.

2. Methods

2.1. Study areas

Fire-caused mortality of white fir (*Abies concolor* [Gord. and Glend.] Lindl.), sugar pine (*Pinus lambertiana* Dougl.), ponderosa pine, incense-cedar (*Calocedrus decurrens* [Torr.] Floren.), and California black oak (*Quercus kelloggii* Newb.) was investigated in 10 ha of the Suwanee prescribed burn unit of Sequoia National Park, California. The burn unit is located on a southeastern aspect with 20–30% slopes, T15S R29E NW 1/4 of section 35, latitude 36°35′, longitude 118°47′42″, between 1830 and 1900 m above sea level, approximately 0.5 km south of the Suwanee Giant Sequoia grove. The Suwannee unit was burned in October of 1992 and flame lengths varied from 0.5 to 3 m within the unit.

Forest composition and density was measured using three randomly placed circular 0.1 ha plots within the unit. The DBH and species were recorded for all snags and live trees with a DBH greater than 2.5 cm. The following plot calculations by species were produced: average basal area per hectare, average number of trees per hectare, average quadratic mean diameter, average percent plot basal area per hectare, and average percent plot stocking (percent of total trees per hectare by species).

Fire-caused mortality of giant sequoia was investigated in two plots of approximately 1 ha each in the Deer Creek prescribed natural fire in Sequoia National Park. The burn plots are located on a northeastern aspect with 10–20% slopes, T17S R30E, latitude 36°27′3″, longitude 118°39′36″, between 2010 and 2070 m above sea level, approximately 3 km south of the Atwell Mill Campground in the Mineral King area of the Sequoia National Park. This fire was started by a lightning strike on 28th September and burned until mid-November 1991. No pre-burn vegetation or fuels data was taken from this area because this fire was not management ignited.

2.2. Fuel measurements

Surface and ground fuels were sampled at 16 locations placed systematically (50 m grid on two north/south transects) within the Suwanee prescribed burn unit to determine stand level fuel loads. Each sample location was marked with a permanent steel stake and three transects with random azimuths were used to inventory surface and ground fuels (Brown, 1974). A total of 48 fuel transects were used to inventory surface and ground fuels.

Time-lag fuels of 1 and 10 h were sampled from 0 to 2 m, 100 h time-lag fuels from 0 to 3 m, and 1000 h time-lag fuels and greater from 0 to 10 m on each transact. Diameter ranges of 1, 10, 100, and 1000 h time-lag fuels are 0–0.63, 0.63–2.54, 2.54–7.62 cm, and greater than 7.62 cm, respectively. Duff and litter depth were measured with two duff pins placed at 2 and 3 m on each transact. Fuel consumption was calculated by subtracting post-burn fuel loads from pre-burn fuel loads for all fuel types. Regression equations were used to convert forest floor depth to mass (Sackett, personal communication, 1995; Stephens, 1995). Regression equations used to convert forest floor depth to mass had r^2 values varying from 0.81 to 0.96.

Forest floor depth at each tree in the Suwanee unit was also measured using duff pins placed approximately 30 cm uphill from each tree. Forest floor depth was measured on the uphill side of the tree because it has been shown to be a better predictor of mortality than measurements from the side-hill or downhill locations (Finney and Martin, 1992). All depth measurements were converted to mass using the same equations referenced above.

Fuel moisture content was sampled within the Suwanee prescribed burn unit 1 h before the burn was ignited. Five samples of duff, litter, 1, 10, and 100 h fuels were randomly taken within the unit and placed in metal soil sampling cans. Samples were taken to the laboratory and dried at 95 °C for 48 h. Moisture content on a dry weight basis was calculated for each sample.

2.3. Mixed conifer mortality

Trees were selected to produce a minimum of five trees per 5 cm diameter class for each species between 5 and 60 cm DBH with the exception of giant sequoia where approximately 100 trees were tagged between 15 and 100 cm DBH, and black oak where maximum DBH was 40 cm. All trees were identified with a steel tag and were within the fuel sampling grid.

Four weeks after burning, the following local fire characteristics were measured on each tree: forest floor consumption in centimeters (duff), percent crown volume scorched (PCVS) (Peterson, 1985), and crown scorch height in meters (scht). All variables were continuous. A height pole or clinometer was used to measure crown scorch height. PCVS was estimated visually. Visual estimates of crown volume scorched are a more accurate measure of fire damage than percent crown length scorched, despite the subjectivity of the estimate by an observer (Peterson, 1985). PCVS varied between 20 and 100% in all species except California black oak where it varied from 50 to 100%. Mortality data were collected annually on individual trees from 1992 to 1995 in the Suwanee unit and tree characteristics are summarized in Table 1.

All appropriate combinations of variables (DBH, PCVS, duff, scht) were used in the logistic regression analysis. No model included both PCVS and scorch height terms because these are not independent measurements of crown injury after fire. Independent variables were included in each model only if they were statistically significant ($P < 0.05$).

Giant sequoia mortality data were collected annually from 1991 to 1995 in the Deer Creek prescribed natural fire. A total of 85 giant sequoias, ranging in DBH from 15 to 100 cm and with a PCVS varying from 25 to 100% were tagged 1 month after the lightning fire (Table 1). Probability of death was modeled using logistic regression analysis as a function of DBH, PCVS, and scht.

The logistic regression equation used to model mortality of the mixed conifer trees species has the form

$$P = \frac{1}{1 + e^{-(\beta_1 + \beta_2 X_2 + \cdots + \beta_K X_K)}} \quad (1)$$

where P is the probability of post-fire mortality, $X_2 - X_K$ are independent variables, and $\beta_1 - \beta_K$ are model coefficients estimated from mortality data.

The SAS LOGISTIC procedure was used to obtain maximum likelihood estimates of equation coefficients (SAS Institute, 1989). Model goodness-of-fit were assessed by the likelihood ratio χ^2 statistic and receiver operations characteristic (ROC) (Saveland and Neuenschwander, 1990). The ROC curve is generated by plotting the hit rate versus the false alarm rate as the decision criterion varies from 0 to 1 (Egan, 1975) and this procedure has been used to assess logistic mortality model performance in other fire investigations (Ryan and Reinhardt, 1988; Finney and Martin, 1992; Regelbrugge and Conard, 1993).

Binary data on tree death was used for analysis. Four different logistic regression models were tested for all species except giant sequoia where no pre-burn forest floor data were available. The first model used DBH, PCVS, and duff to model mortality. The second used DBH, scht, and duff. The third and fourth models

Table 1
Summary of tree characteristics used in mortality modeling

Species	Number of trees	Minimum DBH (cm)	Maximum DBH (cm)	Average DBH (cm)	S.D.
Giant sequoia	85	10	100	39.0	22.7
Incense-cedar	110	5	60	21.7	12.6
Black oak	120	5	40	17.5	6.8
Sugar pine	140	5	60	19.4	13.9
Ponderosa pine	170	5	60	26.3	13.9
White fir	400	5	55	20.3	10.6

were similar to models 1 and 2 with the exception that forest floor consumption (duff) was not included as an independent variable. Models 3 and 4 would be useful in predicting mortality after wildfires or when no pre-burn forest floor data are available. Models were developed using PCVS and scht independently to allow for flexibility in possible future modeling applications.

3. Results

Average pre-fire tree density within the Suwanee prescribed fire unit was 707 trees per hectare (S.E. = 106.5) and average basal area was 83 $m^2\,ha^{-1}$ (S.E. = 2.4). Snags density averaged 60 snags per hectare (S.E. = 16.3). White fir was the most common tree within the plots, contributing 60.4% of basal area and 62.6% of density (Table 2). Incense-cedar was the next most common species, contributing 22.3 and 29.5% of basal area and density, respectively (Table 2).

The last fire recorded in the Suwanee prescribed fire unit occurred in 1898 (Caprio, personal communication 1996). Surface and ground fuel loads averaged 50.65 Mg ha^{-1} (range 0.04–287.25 Mg ha^{-1}) and 179.66 Mg ha^{-1} (range 14.97–788.70 Mg ha^{-1}), respectively (Table 3). In 87% of the fuel transacts, pre-burn fuel loads of the forest floor (ground fuels) were greater than surface fuels loads. Fuel moisture contents were below 10% for all fuels with the exception of duff which averaged 15.8% moisture (Tables 4 and 5).

3.1. Mortality modeling

The majority of the mortality models produced had a significant fuel consumption term (Tables 6–10). The likelihood ratio χ^2 was highly significant ($P < 0.0001$) for all models developed and the ROC varied from 0.736 to 0.997 for all models indicating good overall model performance. None of the logistic regression models developed for California black oak produced a significant maximum likelihood estimate, indicating that the variables measured were not significant predictors of mortality. Figs. 1–3 present probability of mortality at three different diameters (DBH = 10, 25, 50 cm) for ponderosa pine, incense-cedar, and white fir, respectively, sugar pine mortality is presented in Fig. 4.

Table 2
Pre-burn forest structure in the Suwanee prescribed fire unit (S.E.)

Tree species	Average DBH (cm)	Average density (trees per hectare)	Basal area (%)	Density (%)
White fir	29.4 (8.5)	420 (112.7)	60.4	62.6
Incense-cedar	21.6 (4.3)	223.3 (88.9)	22.3	29.5
Sugar pine	34.9 (8.4)	63.3 (29.1)	17.3	7.9

Table 3
Surface and ground fuel loads in the Suwanee prescribed fire unit

Fuel type	Average (Mg ha^{-1})	Range (Mg ha^{-1})	S.E.	Average consumption (%)
1 h time-lag	0.37	0.03–1.56	0.05	97
10 h time-lag	2.99	0–13.27	0.44	89
100 h time-lag	5.16	0–37.04	1.13	87
1000 h time-lag and larger, sound	18.46	0–222.69	6.93	85
1000 h time-lag and larger, rotten	23.65	0–273.90	8.51	99
Total surface fuel	50.65	0.04–287.25	11.11	91
Duff and litter	179.66	14.97–788.70	20.55	93

Table 4
Fuel moisture contents in the Suwanee prescribed fire

Fuel type	Moisture content (%)	S.E.
1 h time-lag	5.5	0.21
10 h time-lag	6.1	0.08
100 h time-lag	6.9	0.44
Litter	7.3	0.51
Duff	15.8	0.24

Table 5
Percent of giant sequoia-mixed conifer tree mortality by year[a]

Species	Death year 1 (%)	Death year 2 (%)	Death year 3 (%)	Death year 4 (%)
Giant sequoia	77	3	3	17
Incense-cedar	81	12	7	N.A.
Black oak	100	0	0	N.A.
Sugar pine	81	13	6	N.A.
Ponderosa pine	82	14	4	N.A.
White fir	64	28	8	N.A.

[a] N.A.: not available, mortality data of 3 years.

4. Discussion

Fire was once common in mixed conifer forests of the Sierra Nevada (Kilgore and Taylor, 1979). Fire suppression and management activities during the 20th century have modified the structure and function of mixed conifer forests of the southern Sierra Nevada (Parsons and DeBendeetti, 1979; Bonnicksen and Stone, 1982; Stephens and Elliott-Fisk, 1998).

Table 6
White fir logistic regression mortality parameters from the Suwannee prescribed fire[a]

Model (white fir)	Parameter							
	β_1	β_2	X_2	β_3	X_3	β_4	X_4	ROC
1	−7.0117 (0.0001)	−0.0659 (0.0001)	DBH	0.1061 (0.0001)	PCVS	0.00488 (0.0024)	Duff	0.968
2, 4	1.0299 (0.0001)	−0.1983 (0.0001)	DBH	0.3374 (0.0001)	scht	N.S./N.A.	Duff	0.809
3	−6.2674 (0.0001)	−0.0503 (0.0013)	DBH	0.1031 (0.0001)	PCVS	N.A.	N.A.	0.958

[a] P-values given in parentheses. N.S.: not significant at $P = 0.05$, N.A.: not applicable.

Table 7
Incense-cedar logistic regression mortality parameters from the Suwannee prescribed fire[a]

Model (incense-cedar)	Parameter							
	β_1	β_2	X_2	β_3	X_3	β_4	X_4	ROC
1, 3	−12.0408 (0.0007)	−0.061 (0.0456)	DBH	0.1554 (0.0001)	PCVS	N.S./N.A.	Duff	0.958
2, 4	1.2721 (0.0126)	−0.1492 (0.0003)	DBH	0.3373 (0.0048)	scht	N.S./N.A.	Duff	0.770

[a] P-values given in parentheses. N.S.: not significant at $P = 0.05$, N.A.: not applicable.

Table 8
Sugar pine logistic regression mortality parameters from the Suwannee prescribed fire[a]

Model (sugar pine)	Parameter							
	β_1	β_2	X_2	β_3	X_3	β_4	X_4	ROC
1, 3	−11.241 (0.0001)	N.S.	DBH	0.146 (0.0001)	PCVS	N.S./N.A.	Duff	0.979
2	N.S.	−0.2084 (0.0001)	DBH	0.3870 (0.0001)	scht	0.0154 (0.0229)	Duff	0.808
4	N.S.	−0.1736 (0.0001)	DBH	0.3838	scht	N.A.	N.A.	0.748

[a] P-values given in parentheses. N.S.: not significant at $P = 0.05$, N.A.: not applicable.

Table 9
Ponderosa pine logistic regression mortality parameters from the Suwannee prescribed fire[a]

Model (ponderosa pine)	Parameter							
	β_1	β_2	X_2	β_3	X_3	β_4	X_4	ROC
1	−6.5866 (0.0044)	−0.0812 (0.0001)	DBH	0.0836 (0.0002)	PCVS	0.0163 (0.0012)	Duff	0.869
2	1.7188 (0.0003)	−0.1370 (0.0001)	DBH	0.1379 (0.0138)	scht	0.0082 (0.048)	Duff	0.767
3	−3.155 (0.0357)	−0.0410 (0.0062)	DBH	0.0550 (0.0002)	PCVS	N.A.	N.A.	0.829
4	2.0709 (0.0001)	−0.1296 (0.0001)	DBH	0.1686 (0.0018)	scht	N.A.	N.A.	0.736

[a] P-values given in parentheses. N.A.: not applicable.

Table 10
Giant sequoia logistic regression mortality parameters from the Deer Creek prescribed natural fire[a]

Model (giant sequoia)	Parameter					
	β_1	β_2	X_2	β_3	X_3	ROC
3	−166.51 (0.0038)	N.S.	DBH	1.7296 (0.0038)	PCVS	0.997
4	1.7071 (0.0382)	−0.0852 (0.0004)	DBH	N.S.	scht	0.836

[a] P-values given in parentheses. N.S.: not significant at $P = 0.05$.

The absence of fire in the southern Sierra Nevada during the last century has produced a forest dominated by shade tolerant species (Parsons and DeBendeetti, 1979). Fuel loads measured in the Suwanee unit are large and are similar to other areas that have not burned in the last century (Peterson et al., 1994). Post-fire fuel inventory indicated that the majority of ground and surface fuels were consumed during the prescribed fire (Table 3).

The forest floor was almost completely consumed by the prescribed fire. This is consistent with predictions of total forest floor consumption at moisture contents below 30% (Sandberg, 1980; Brown et al., 1985). Other studies have also determined that duff combustion and basal injury to ponderosa pine are affected by duff depth and duff moisture content during burning (Ryan and Frandsen, 1991). Forest floor combustion occurs slowly but prolonged heat can

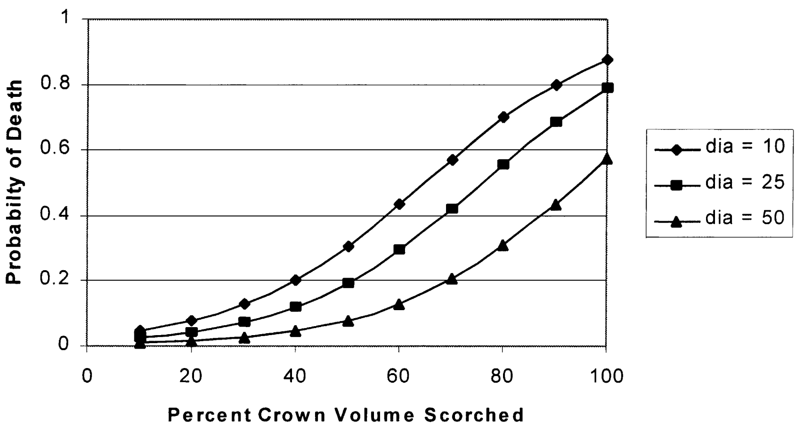

Fig. 1. Probability of mortality of ponderosa pine after the Suwanee prescribed fire (model 3).

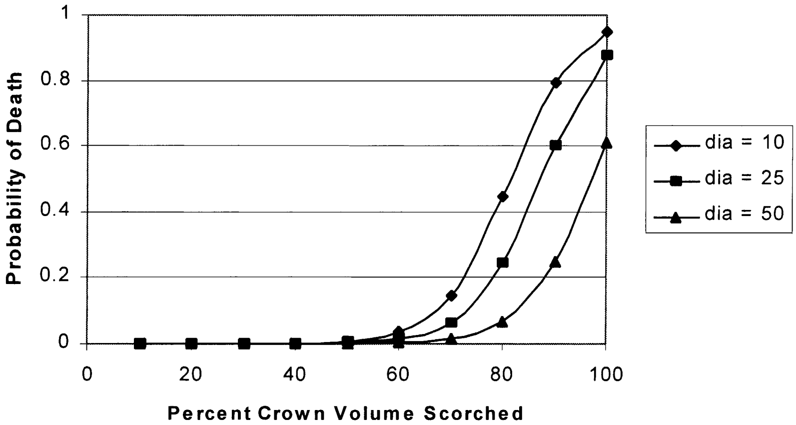

Fig. 2. Probability of mortality of incense-cedar after the Suwanee prescribed fire (model 3).

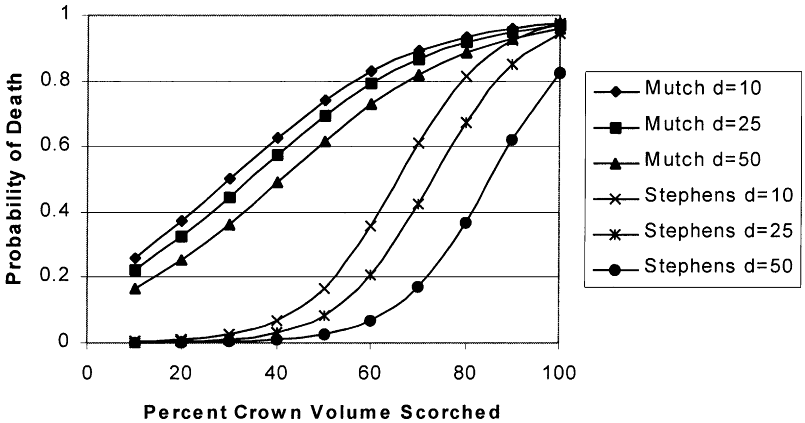

Fig. 3. Probability of mortality of white fir (Stephens (model 3)—this work; Mutch—Mutch and Parsons, 1998).

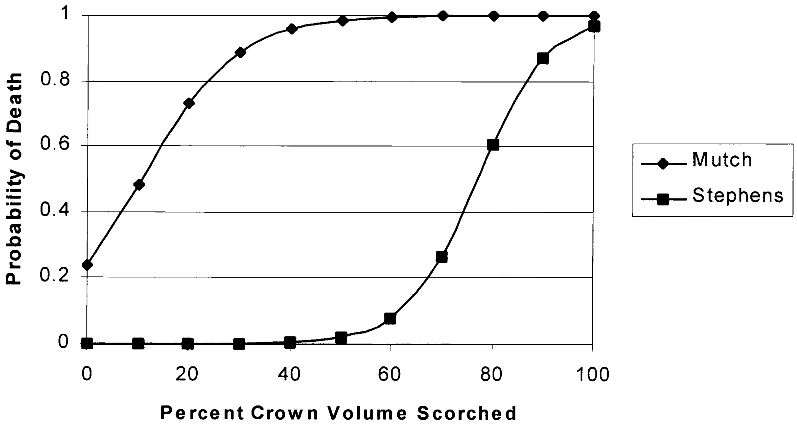

Fig. 4. Probability of mortality of sugar pine (Stephens (model 3)—this work; Mutch—Mutch and Parsons, 1998).

damage stems and roots independent of the period of flaming combustion.

PCVS was a significant predictor of mortality for all conifer models developed because scorching reduces the amount of live crown available for photosynthesis. Photosynthate production per unit area varies depending on crown location, with 1-year-old needles in the middle and lower crowns of ponderosa pine producing approximately 70 and 50%, respectively, of that in the upper crowns (Helms, 1970). Loss of the less efficient, lower tree crown by scorching will therefore, reduce transpiration demand but photosynthate production will remain relatively high since the most efficient tissues will remain (Wyant, 1981).

None of the logistic regression models developed for California black oak produced a maximum likelihood estimate. California black oak is susceptible to cambial injury because of thin bark. Following top-killing, 90% of the California black oaks sprouted from the root collar regardless of forest floor consumption, PCVS, or scht. These results are similar to that reported by Regelbrugge and Conard (1993). For all species, the majority of tree death occurred within 2–3 years after fire (Table 5) and this is consistent with other published studies (Wagener, 1961; Dieterich, 1979).

Young-growth giant sequoia has the ability to survive extreme crown scorch. No mortality occurred in giant sequoias that had PCVS less than 90% and the logistic regression equation developed for giant sequoia predict low probabilities of mortality until PCVS exceeds 90–95%. In many cases, the crown that was originally scorched in 1991 has re-grown from epicormic shoots and live crown volume increased approximately 10–15% by 1995. All giant sequoias that had 100% PCVS died in this study, indicating trees of this size did not recover from complete crown scorch. Consumption of forest floor fuels near the giant sequoia trees could have contributed to this mortality.

Probability of death is lower for giant sequoia, incense-cedar, and ponderosa pine at high levels of PCVS when compared to sugar pine and white fir. Ponderosa pine, white fir, and sugar pine had significant forest floor consumption variables and inclusion of this term improved or slightly improved model performance (Tables 6, 8 and 9). Crown damage is still the dominant factor in the mortality equations but forest floor consumption was significant in three of four conifer species studied.

DBH was a significant parameter in all mortality models developed with the exception of giant sequoia and sugar pine. The insignificant DBH term in the giant sequoia model may be a result of giant sequoia's ability to resist high amounts of crown damage. In this study, all giant sequoia trees with PCVS less than 90% survived and this was independent of DBH.

The insignificant DBH term in the sugar pine model is consistent with an independent study in the Crescent Meadow area of Sequoia National Park (Mutch and Parsons, 1998). Mutch and Parsons used logistic regression to predict mortality of sugar pine and white fir and determined PCVS was the only significant parameter in the sugar pine model developed; PCVS and DBH were significant in the white fir fire caused mortality model. The season of prescribed fire was similar in both Mutch and Parsons (1998) and this work.

Mutch and Parsons (1998) logistic regression mortality equations are included in Figs. 3 and 4 along with the equations developed from this work. Mutch and Parsons (1998) probability of mortality is high for sugar pine at very low levels of PCVS (probability of mortality $= 0.48$ at PCVS $= 10$; probability of mortality $= 0.97$ at PCVS $= 50$). In contrast, mortality equations developed from this work predict a low probability of mortality at PCVS $< 60\%$. As PCVS increases above 60%, the probability of mortality increases sharply. Low probabilities of mortality corresponding to low amounts of overstory damage have been found in other conifer species (Ryan, 1982; Ryan and Reinhardt, 1988; Ryan et al., 1988; Finney and Martin, 1992; Regelbrugge and Conard, 1993). Low mortality rates at low crown damage levels are also consistent with studies that determined removal of less efficient lower tree crowns did not result in high mortality (Helms, 1970; Wyant, 1981). No studies have reported high probabilities of mortality (above 0.25) at low levels of crown damage (PCVS less than 10%).

White pine blister rust (*Cronartium ribicloa* Fisch.) was observed in the study area and this pathogen has caused wide spread mortality of sugar pine. Trees with multiple non-lethal rust infections may be weakened to the point that they are killed by other agents (Smith, 1996). Reduction in tree vigor by white pine blister rust may make sugar pine more susceptible to damage from prescribed fires. This may be one explanation of why the sugar pine logistic regression model developed in this study did not have a significant DBH term.

Mutch and Parsons (1998) used a lower DBH limit of 1 cm and their diameter distributions for the two species studied was skewed to smaller trees (Mutch, personal communication, 1999). This could have resulted in the prediction of higher probabilities of mortality because very few small trees would have survived the prescribed fire. In this study, trees were selected to produce a relatively even DBH distribution over the size range of each species and the minimum DBH was 5 cm. Mutch and Parsons (1998) did have similar maximum DBH ranges when compared to this work. The skewed diameter distributions of the trees sampled by Mutch and Parsons (1998) probably led to biased mortality predictions.

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