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Postfire Mortality of Ponderosa Pine and Douglas-fir:

A Review of Methods to Predict Tree Death

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Abstract

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This review focused on the primary literature that described, modeled, or predicted the probability of postfire mortality in ponderosa pine *(Pinus ponderosa)* and Douglas-fir *(Pseudotsuga menziesii)*. The methods and measurements that were used to predict postfire tree death tended to fall into two general categories: those focusing on measuring important aspects of fire behavior, the indirect but ultimate cause of mortality; and those focusing on tissue damage due to fire, the direct effect of fire on plant organs. Of the methods reviewed in this paper, crown scorch volume was the most effective, easiest to use, and most popular measurement in predicting postfire mortality in both conifer species. In addition to this direct measure of foliage damage, several studies showed the importance and utility of adding a measurement of stem (bole) damage. There is no clear method of choice for this, but direct assessment of cambium condition near the tree base is widely used in Douglas-fir. Only two ponderosa pine studies directly measured fine root biomass changes due to fire, but they did not use these measurements to predict postfire mortality. Indirect measures of fire behavior such as ground char classes may be the most practical choice for measuring root damage. This review did not find clear postfire survivability differences between the two species. The literature also does not show a consistent use of terminology; we propose a standard set of terms and their definitions.

Key words: *Pinus ponderosa, Pseudotsuga menziesii,* wildfire, prescribed burn, crown scorch, bole char, ground char, fire intensity

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Contents

Introduction

From the earliest days of forest management in the United States, foresters have been confronted with the problem of identifying which trees will survive after fire. Initial commercial interest focused on delayed wildfire effects, but as prescribed fire became more popular, its effects on tree mortality also became part of the question. Salvage timber harvests were aimed both at trees directly killed by wildfire and those that could be predicted to die within a few years due to tissue damage by fire. Concerns about potential insect outbreaks in fire damaged trees, changes in wildlife habitat quality, and aesthetic issues developed as management objectives changed through time.

Ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) are two commercially and ecologically important tree species in the Western United States. Both species occur in forest types subject to periodic wildfires, and both species develop a thick insulating bark as they age. Douglas-fir generally occurs on more mesic sites that historically burned less frequently than most ponderosa pine-dominated sites; regardless, prescribed burning is a common management practice in forest types dominated by both species (Pyne and others 1996). The studies reviewed in this paper (fig. 1) investigated postfire mortality of these species using a variety of methods to directly and indirectly measure fire damage to tree tissue. As yet, no consensus has developed on which methods are the most accurate or practical in predicting short-term postfire mortality. This lack of consensus is due in part to confounding issues related to the studies themselves, such as differences in study sites, pre- and postfire environments, varying fire severities and seasonality, plus differences in tree sizes and stand densities. The purpose of this literature review is to gather information on the methods used to evaluate postfire mortality in ponderosa pine and Douglas-fir and to evaluate the accuracy and efficiency of those methods.

Our approach was to focus on empirical papers from the primary literature, mostly journal articles and government documents, and to give much less weight to management notes, marking guides, reviews, and anecdotal reports. We evaluated the study design, sample size, data analysis, and results of each article while disregarding discussion points, conclusions, and recommendations unless they were clearly supported by the results. The common practice of including results and discussion within the same section of paper made this task difficult at times. Note that results and conclusions presented by authors that were not clearly supported by data were intentionally omitted from the synthesis part of this review.

The synthesis part of this review is organized primarily by fire damage to major plant organs: leaves/foliage, stems/bole, and roots. Within each category, an overview of methods is followed by a detailed, somewhat chronological, discussion of each method of fire

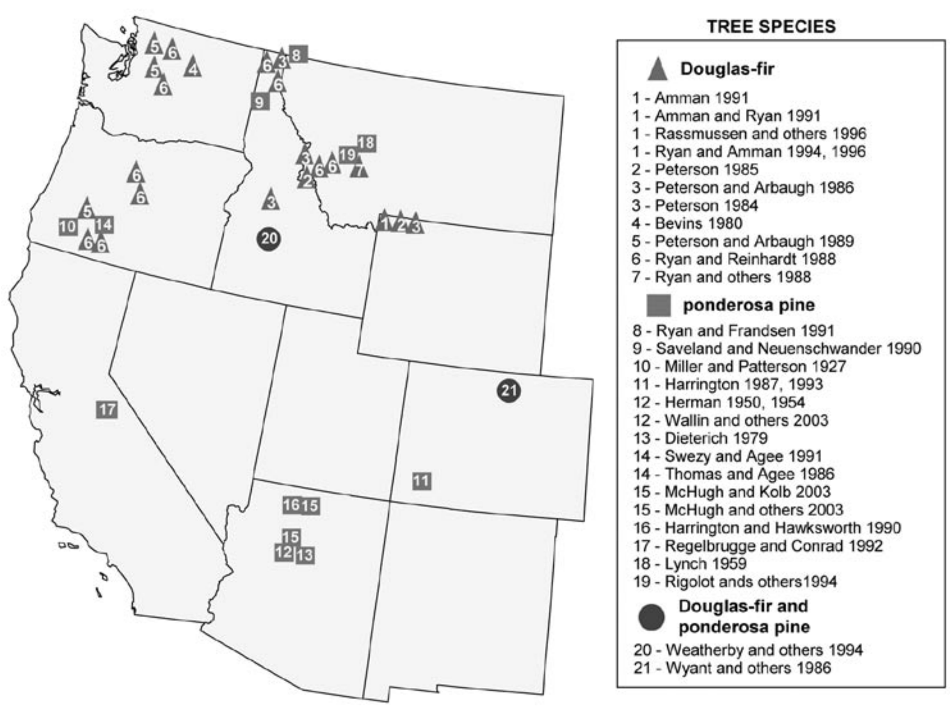

Figure 1—Locations of the most often cited postfire mortality field studies.

damage measurement, grouped by species when possible. The synthesis is followed by an annotated bibliography in which papers may be annotated separately, as a series of papers on the same long-term study, or on a common theme by the same author(s). The annotated bibliography has most of the reports cited in the text. Additional related references are listed at the end of this review.

Fire Damage Measurements

As we examined the various fire damage measurements it became apparent that there were two general categories. Some workers tried to predict tree mortality indirectly via fire behavior parameters: that is, using the ultimate cause of the damage. Others measured tree tissue damage directly in order to predict mortality: that is, concentrating on the proximal effect of the fire. Ground char, bole char, bole scorch height, and crown scorch height are examples of the former; crown scorch volume, crown consumption volume, direct observation of cambium condition, and fine root kill are examples of the latter. Fire behavior variables are obviously important when writing fire prescriptions and predicting mortality before the fire; however, after the fire, more direct tissue damage measurements may be more accurate. This is apparently the case when crown scorch height is compared to crown scorch volume, as discussed in the next section.

Most of the studies we reviewed measured tree mortality one or more times during the first 3 years postfire. Only two studies measured mortality during the first 3 years and after a longer period of time, 8 years in this case: Lynch (1959) for ponderosa pine and Ryan and others (1988) for Douglas-fir. The clearest indication of when most postfire mortality occurs is from the latter studies and from Miller and Patterson (1927). These three studies show that most postfire mortality occurs by the end of the second postfire year.

Foliage/Terminal Buds

All but one of the papers listed in table 1 used some measure of foliage/terminal bud damage to investigate postfire mortality, and these measures were often the most explanatory or had the greatest predictive power for tree death. There seem to be three basic fire effects concepts embodied in these variables: scorching and thus killing of foliage, bud kill, and consumption of leaves and buds. Table 1 shows a diverse set of variable names. Most papers lack clear definitions of what is meant by these variables, other than literal meanings and the context in which they are written. Scorch height as used in these papers (for example, Bevins 1980; Peterson 1985; Ryan and Reinhardt 1988) seems to imply the maximum or mean height of foliage scorch and thus leaf kill. Scorch volume would again refer to foliage scorch (for example, Peterson 1985; Weatherby and others 1994) but could also include bud kill and consumption if it was present and not clearly separated out by definition or by other variables in the same study (for example, McHugh and Kolb 2003; Wyant and others 1986). The word "kill," unless defined (for example, Ryan and Reinhardt 1988), could refer to leaf scorch, bud kill, and/or consumption of either. In the absence of specific data collected in that study for consumption or bud kill, crown kill must indicate all of the above. For example, Herman (1950, 1954) used a variable called "length of crown kill" without definition: in other words, there was no mention of terminal buds or separation of consumption and scorch. Presumably these concepts were lumped together.

Two of the earliest investigations of postfire mortality focused on western pine beetle *(Dendroctonus brevicomis)* induced mortality of ponderosa pine by fire injury class (Miller and Patterson 1927; Salman1934). Miller and Patterson (1927) explicitly combined scorch and consumption of leaves and terminal buds into five clearly defined qualitative damage categories and found that ponderosa pine trees with almost complete foliage consumption and terminal bud kill but with live cambium (injury class 4) died the first year after fire. In their moderate injury class (3) with most of the foliage scorched, no bud kill, and with some cambial damage, tree survival rate was 8 percent the third year postfire with all postfire mortality being attributed to bark beetles. Ponderosa pine trees with partial foliage scorch (injury class 2) had 92 percent survival (Miller and Patterson 1927). Salman (1934) presented eight fire damage classes ranked by increasing defoliation and cambium injury with a corresponding increase in susceptibility to insect attack and increasing mortality.

Two papers explicitly combined foliage scorch and bud kill in Douglas-fir into a quantitative variable called "percent of prefire crown volume killed," but they did not mention consumption (Ryan and others 1988; Ryan and Reinhardt 1988). Although Ryan and others (1988) used the term "crown scorch" without definition, the data in that paper were a subset of the larger dataset in Ryan and Reinhardt (1988), which used the term "crown volume killed," with crown clearly referring to buds and foliage. They found that percent crown volume killed was a significant variable but ranked below number of dead cambium quadrants in logistic regression modeling

Table 1—Measurements as originally used by authors to assess fire damage to foliage and buds, stems, and roots of ponderosa pine (*Pinus ponderosa)* or Douglas-fir (*Pseudotsuga menziesii*). Note that root damage measurements are indirect.

Area of damage ***Measurement*/species**	**Citation**
Foliage/buds	
Percent crown scorch: volume	
Ponderosa pine	Cluck and Smith 2001, Dieterich 1979[1,] McHugh and Kolb 2003, McHugh and others 2003, Saveland 1982, Saveland and Neuenschwander 1990, Wallin and others 2003, Weatherby and others 1994
Douglas-fir	Lynch 1959[1], Peterson 1984, 1985, Peterson and Arbaugh 1986, 1989, Ryan and others 1988, Spicer 1984, Weatherby and others 1994
Percent crown consumed: volume	
Ponderosa pine	McHugh and Kolb 2003, McHugh and others 2003
Crown consumption	
Ponderosa pine	Dieterich 1979
Percent crown consumption: height	
Ponderosa pine and Douglas-fir	Wyant and others 1986
Percent crown killed: volume	
Douglas-fir	Ryan and Reinhardt 1988
Percent crown scorch: height	
Ponderosa pine	Harrington 1993
Douglas-fir	Bevins 1980
Percent crown scorch: length	
Ponderosa pine	Harrington and Hawksworth 1990, Wyant and others 1986
Douglas-fir	Wyant and others 1986
Percent of live crown kill: length	
Ponderosa pine	Herman 1950, 1954
Scorch height: maximum	
Ponderosa pine	Saveland and Neuenschwander 1989, 1990, Saveland 1982, Wyant and others 1986
Douglas-fir	Bevins 1980, Peterson 1984, Ryan and others 1988, Spicer 1982, Wyant and others 1986,
Scorch height: mean	
Douglas-fir	Peterson 1985, Peterson and Arbaugh 1986, 1989,
Damage classes	
Ponderosa pine	Miller and Patterson 1927, Salman 1934
Length of green crown	
Ponderosa pine	Mitchell 1914
Stems	
Bole char: height	
Ponderosa pine	Herman 1950, 1954, McHugh and Kolb 2003, Regelbrugge and Conard 1993, Weatherby and others 1994
Douglas-fir	Weatherby and others 1994
Percent bole char: height	
Ponderosa pine	Wyant and others 1986
Douglas-fir	Wyant and others 1986
Bole char severity	
Ponderosa pine	McHugh and Kolb 2003
Bole char intensity	
Ponderosa pine	Weatherby and others 1994
Douglas-fir	Weatherby and others 1994
Bole char classes	
Ponderosa pine	Harrington and Hawksworth 1990
Percent basal scorch/char	
Ponderosa pine	Weatherby and others 1994
Douglas-fir	Peterson 1984, Peterson and Arbaugh 1986, 1989, Weatherby and others 1994
Bark char depth	
Douglas-fir	Peterson and Arbaugh 1986, 1989

Table 1—*Continued*.

Area of damage *Measurement*/species	Citation
Bark char ratio	
Ponderosa pine	Peterson 1984, Peterson and Arbaugh 1986, 1989
Cambium condition	
Douglas-fir	Peterson and Arbaugh 1989, Ryan and others 1988
Visible cambium injury	
Ponderosa pine	Herman 1950, Miller and Patterson 1927, Salman 1934
Resin flow	
Ponderosa pine	Wallin and others 2003
Insect attack	
Ponderosa pine	Weatherby and others 1994
Douglas-fir	Weatherby and others 1994
Insect attack rating	
Ponderosa pine	McHugh and Kolb 2003, McHugh and others 2003
Insect damage	
Douglas-fir	Peterson and Arbaugh 1986, 1989
Insect colonization	
Ponderosa pine	Wallin and others 2003
Bark beetle presence	
Ponderosa pine	Herman 1950, 1954
Roots	
Ground fire severity/ground char	
Ponderosa pine	McHugh and Kolb 2003
Fire severity: litter/duff	
Douglas-fir	Peterson 1984
Ground fire intensity	
Ponderosa pine	Weatherby and others 1994
Douglas-fir	Weatherby and others 1994
Burned area under dripline	
Ponderosa pine	Weatherby and others 1994
Douglas-fir	Weatherby and others 1994

[1] Unclear methods: volume or height

of Douglas-fir mortality (n=166) 8 years postfire in Montana (Ryan and others 1988). In a greatly expanded dataset with 43 prescribed fires, seven conifer species including Douglas-fir, and 2,356 trees, they found that bark thickness and crown kill were the most significant variables in logistic regression models (Ryan and Reinhardt 1988).

Other workers separated measures of consumption and scorch (Dieterich 1979; McHugh and Kolb 2003; McHugh and others 2003; Wyant and others 1986). Wyant and others (1986) used consumption height whereas the other papers used consumption volume; no one has separated consumption of buds and leaves. Dieterich (1979) found that four of the seven ponderosa pine trees with some crown consumption in his study were dead within 3 years after a fall fire in northern Arizona. In a larger northern Arizona study, mortality rates by level of crown consumption were 67 percent mortality at 30 percent crown consumption and 100 percent mortality at 60 percent crown consumption (McHugh and Kolb 2003, n = 1367). In a separate paper, McHugh and others (2003) combined crown consumption and crown scorch volume into a variable called total crown damage for logistic regression modeling to predict probability of mortality 3 years postfire. Total crown damage was paired with insect attack rating as a predictive model of postfire mortality.

In a Colorado study, crown consumption variables, measured by quadrant to indicate asymmetric fire damage, were significant contributors to broad multivariate discriminant functions that characterized differences between live and dead ponderosa pine and Douglas-fir trees 2 years after prescribed fire (Wyant and others 1986). In this study, crown consumption variables ranked fourth (out of nine to 10 variables) for both species (percent uphill quadrant for ponderosa pine and percent downhill quadrant for Douglas-fir), which was below crown scorch variables for ponderosa pine *and* Douglas-fir as well as below bole char variables for ponderosa pine.

Many of the publications in table 1 emphasized some variation of the term crown scorch, which probably encompassed consumption and bud kill when present. Of the publications that used scorch height measured from ground level, most used maximum scorch height (Bevins 1980; Peterson 1984, 1985; Peterson and Arbaugh 1986, 1989; Ryan and others 1988; Saveland 1982; Saveland and Neuenschwander 1989, 1990; Swezy and Agee 1991; Wyant and others 1986). Peterson (1985) and Peterson and Arbaugh (1986, 1989) also used mean scorch height.

Mitchell (1914) measured length of green crown after fire, but most investigators have used scorch length or heights. Saveland (1982) and Saveland and Neuenschwander (1990) (table 1) found that scorch height and diameter at breast height (dbh) were good indicators of ponderosa pine mortality (n = 194) in northern Idaho, although the latter paper found that crown scorch volume was the best predictor. Several workers used length of live crown scorched expressed as percent of original live crown length (Harrington 1993; Harrington and Hawksworth 1990; Herman 1950, 1954; Spicer 1982). Harrington's (1993) paper focused on season of prescribed burn effects, but also found a distinct threshold for increased mortality above 70 percent crown scorch in ponderosa pine 4 years after fire. Harrington and Hawksworth (1990) found that dbh and crown scorch length were significant independent variables in a logistic regression postfire mortality model and that high dwarf mistletoe (*Arceuthobium vaginatum*) ratings, while not significant at the $p = 0.05$ level, tended to cause higher scorch levels. Herman (1954) found that length of crown kill, dbh, and severity of fire were better indications of postfire mortality in ponderosa pine than bark beetle presence, height of bark scorch, or presence of nearby burned out stumps. The only Douglas-fir paper to use percent crown scorch length (Spicer 1982) found it to be a better indicator of mortality than crown scorch height or bark scorch height.

Bevins (1980) used maximum scorch height as the only fire damage variable but also included tree diameter (dbh) to model probability of Douglas-fir postfire survival. However, when scorch height was directly compared with other fire damage variables, it was less accurate than crown scorch volume for Douglas-fir (Peterson 1984, 1985; Peterson and Arbaugh 1986, 1989) and was "clearly a poor discriminator" compared to 15 other fire damage parameters in ponderosa pine (Wyant and others 1986).

Many investigators who used measures of scorch height also used crown scorch volume, visually estimating the volume scorch as a percent of original crown volume (table 1). Some used crown scorch volume (which may include some crown consumption) as their only measure of postfire foliage damage (Cluck and Smith 2001; McHugh and Kolb 2003; McHugh and others 2003; Wallin and others 2003; Weatherby and others 1994). Most workers who compared the efficacy of crown scorch volume to other fire damage variables in predicting postfire mortality found that it was the most accurate for both ponderosa pine *and* Douglas-fir (McHugh and others 2003; Peterson 1984; Peterson and Arbaugh 1986, 1989; Saveland and Neuenschwander 1990; Weatherby and others 1994). These workers also found that some measure of bole char was the second most important measurement, except for two studies which did not measure fire bole damage (McHugh and others 2003; Saveland and Neuenschwander 1990). The only paper we reviewed that did not rank crown scorch volume as the most accurate was Ryan and others (1988) (although the introduction section of Ryan and Reinhardt [1988] in citing Ryan and others [1988] stated that it was), but, even here, it was better than scorch height. Interestingly, Peterson (1985) found that Douglas-fir crown scorch volume, calculated from mean scorch height and crown shape measurements, was less accurate than visual estimates of crown scorch volume.

Stems

As noted in the previous section, two early papers investigating postfire mortality combined crown and cambium injury into qualitative damage classes to analyze postfire mortality (Miller and Patterson 1927; Salman 1934). In ponderosa pine trees with 75 to 100 percent fire defoliation, Salman (1934) showed the strong mortality influence of cambial injury by an increase in mortality from 19.2 percent for trees with "none-to-slight" cambial injury to 72.2 percent with "moderate-to-heavy" cambial injury. However, he provided no raw data on sample sizes or criteria for cambium damage classes. Miller and Patterson (1927) did provide criteria for fire damage classes in ponderosa pine that combined information on bole blackening, cambial damage, foliage scorch, and bud kill. However, they did not give fire mortality rates due to their emphasis on bark beetle infestation. Herman (1950) mentioned collecting data on "extent of visible injury to the cambium at stump height" but provided no data in this or his followup paper (Herman 1954).

More recent papers on Douglas-fir have used chemical tests for the enzyme perioxidase to indicate live/dead cambium layers taken from four increment borer samples: upslope, downslope, and both cross-slopes (Peterson and Arbaugh 1989; Ryan and others 1988). In these studies, either the numbers of live quadrants (Peterson and Arbaugh 1989) or the numbers of dead quadrants were recorded (Ryan and others 1988). Ryan and others (1988) found that number of dead quadrants at 1.4 m (4.6 feet) was significantly higher in spring prescribed fires compared to fall fires and that number of dead quadrants was the best univariate predictor of Douglas-fir tree mortality (n = 166) when compared with dbh, crown scorch height, and crown scorch volume. However, cambial damage would be expected to be a more important mortality predictor in prescribed burns where crown damage may be minimal. Predictive ability was also improved in multivariate logistic regression models that added crown scorch volume, season of burn and/or dbh to number of dead quadrants (Ryan and others 1988). Peterson and Arbaugh (1989) concurred with Ryan and others (1988) by presenting a logistic regression mortality model with significant variables for number of live cambium quadrants and crown scorch volume to predict postwildfire mortality of Douglas-fir (n = 294).

Indirect measures of cambial damage are more common (table 1) and are variations on the theme of bark scorch/char, from both height and circumference perspectives. Ryan (1982a) described the relationship between bark thickness and the duration of fire necessary to cause cambial mortality in ponderosa pine and Douglas-fir and indicated that bark char alone is a poor indicator of cambial damage. Despite the qualitative differences between dictionary definitions of scorch and char, the terms have been used somewhat interchangeably. For example, Regelbrugge and Conard (1993) define height of stem-bark char as "distance from groundline to the highest point of bole blackening," which could include a change in color or texture associated with a scorch definition as well as including the charcoal concept of charring. McHugh and Kolb (2003) and probably, although not crystal clear, Weatherby and others (1994) used Ryan's (1982b) bole char depth classes, which describe the continuum between no scorch to deeply charred. Harrington and Hawksworth (1990) used a similar approach.

Several investigators used maximum bark scorch/char height or char height as a percentage of tree height to measure/predict postfire mortality (table 1). Two papers presented no data or analysis of scorch height (Herman 1950; Weatherby and others 1994). However, Herman's (1954) followup paper stated that height of bark scorch did not show a close relationship with survival in ponderosa pine (n = 235). In contrast, four other studies showed the significant influence of stem/bole char height on postfire mortality. Significantly higher windward stem/bole char heights were found in dead ponderosa pine after fire (McHugh and Kolb 2003, n = 1367; Wyant and others 1986, n = 95). McHugh and Kolb (2003) also found that leeward bole char was significantly higher in dead ponderosa pine. Wyant and others (1986) showed similar results for ponderosa pine (n = 95) for uphill and downhill quadrants as well as in Douglas-fir (n = 103) for windward, leeward, uphill, and downhill quadrants. Regelbrugge and Conard (1993) presented two logistic regression models to predict mortality of ponderosa pine trees following burning: the two-variable model included dbh and height of stem/bark char as significant variables, and the univariate model ($p \leq 0.0001$) used relative char height (char height as a percent of tree height). Wyant and others (1986) also found that bole char height variables were significant components of multivariate discriminant functions to separate live *and* dead Douglas-fir *and* ponderosa pine after prescribed fire, but that their discriminating power was less than that for crown scorch variables.

Several papers included measures of basal scorch/char circumference, expressed as a percentage of total circumference (Peterson 1984; Peterson and Arbaugh 1986, 1989; Weatherby and others 1994). Apparently no one has combined circumference and height measurements to estimate bole surface area damaged by fire. Peterson's (1984) contingency table analysis of 302 Douglas-fir trees 1 year after the 1981 wildfire season showed that basal scorch in combination with crown scorch volume had a "prominent survival threshold" at less than 70 to 90 percent crown scorch volume and less than 70 percent basal scorch. Peterson and Arbaugh (1986) also included basal scorch as a significant parameter in a multivariate discriminant function with and without crown scorch volume for Douglas-fir. In contrast, basal scorch was not included as a significant variable in a logistic regression model using the same 302 Douglas-fir trees from the 1981 fires in a later paper (Peterson and Arbaugh 1986) or from an analysis of a separate 294 Douglas-fir trees from 1982 fires (Peterson and Arbaugh 1989). Weatherby and others (1994) analyzed their percent basal scorch data as part of a bole char rating variable (see next paragraph). In an experimental approach to basal scorch, Rigolot and others (1994) found that for 36 young, vigorous ponderosa pine trees with an average dbh of 18.5 cm (7.3 inches), 85 to 100 percent girdling by artificial heat was necessary to kill them.

Harrington and Hawksworth (1990) showed increasing mortality with increasingly severe bole char ratings in ponderosa pine. McHugh and Kolb (2003) found significant differences in bole char severity (depth classes Ryan 1982b) between live and dead ponderosa pine trees 3 years postfire. Weatherby and others (1994) did not analyze their bole char intensity data directly but multiplied it by percent basal scorch (as noted above) to get a bole char rating prior to analysis. They showed that bole char ratings for fire-killed Douglas-fir and ponderosa pine were significantly higher than for beetle-killed as well as for live trees.

Bark char depth and bark char ratio, char depth as a proportion of original bark thickness, have also been used as variables to predict postfire mortality of Douglas-fir (Peterson 1984; Peterson and Arbaugh 1986, 1989) (table 1). Bark thickness and bark char ratio were found to be important variables in all three papers. As crown scorch volume level increases from 30 to 90 percent, bark char ratio had an increasing effect on Douglas-fir mortality (Peterson 1984). These parameters were also included as significant variables in multivariate discriminant functions with and without crown scorch volume for Douglas-fir (Peterson and Arbaugh 1986) and in predictive logistic regression models (Peterson and Arbaugh 1986, 1989).

A long standing concern of forest managers is the potential increase in mortality by insects, primarily species of *Dendroctonus* (bark beetles) and *Ips* (pine engraver beetles), following fire, both on fire-damaged trees and nearby undamaged trees (Connaughton 1936; Flanagan 1996; Fischer 1980; Furniss 1965; Miller and Patterson 1927; Miller and Keen 1960; Salman 1934; Wagener 1961). Consequently, many investigators of postfire mortality in Douglas-fir and ponderosa pine have included insect damage variables in their studies (table 1). While the focus here is on fire mortality per se, not on physiological fire-response variables, we found one paper that is directly applicable to secondary fire effect and tree resistance to colonizing *Dendroctonus*. Wallin and others (2003) measured the amount of constitutive and induced resin flow in response to experimental mechanical injury following prescribed fire in northern Arizona ponderosa pine and found that both constitutive and induced resin flow were significantly and inversely related to crown scorch volume: in other words, trees with less crown scorch volume had higher potential to "pitch out" colonizing insects.

Miller and Peterson (1927) investigated western pine beetle (*D. brevicomis)* induced mortality of ponderosa pine trees following fires in California and Oregon. However, they synonomized beetle attack with tree death and did not evaluate delayed fire mortality in their slight and moderate damage classes. An early paper by Herman (1950) used the presence/absence of bark beetles as one of a set of variables to investigate postfire mortality on 235 ponderosa pine trees in northern Arizona. On 89 trees that had more than 50 percent crown length killed, he found greater than 75 percent mortality on trees with bark beetles at 3 months postfire compared to less than 50 percent mortality on trees without bark beetles. On the other hand, by the end of the study Herman (1954) concluded that "damage to crown and severity of fire provide a more reliable index to mortality than does presence or absence of beetles."

McHugh and Kolb (2003) and McHugh and others (2003) designed insect attack ratings for postfire ponderosa pine trees in northern Arizona by examining the first 2 m (6.4 feet) of the bole for strip attacks, mass attacks, or no attack. The former two categories were separated by less than or greater than 75 percent of the circumference showing evidence of pine bark beetles, measured by removing small patches of bark. They found significantly higher insect ratings in dead trees from three separate fires (n = 272, 312, 833). McHugh and others (2003) presented a logistic regression model with total crown damage and insect damage as significant variables. That is, in three fires, trees attacked by beetles had greater total crown damage and crown scorch than unattacked trees.

In an experimental approach to the investigation of secondary insect damage effects on postprescribed fire mortality on 40 ponderosa pine trees in northern Arizona, Wallin and others (2003) found that the use of a synthetic pheromone lure for western pine beetles increased the number of both successful and unsuccessful colonization attempts in all crown scorch volume classes. Specifically, they found that ponderosa pine trees with greater than 75 percent crown scorch volume and pheromone lures had western pine beetle brood signs and were dead by 2 years postfire. However, 25 to 50 percent crown scorch volume trees with the same lure had no western pine beetle brood signs and were still alive at the end of year 2. Note that the above results are descriptive and were not statistically analyzed.

Peterson and Arbaugh (1986, 1989) measured postfire insect damage to Douglas-fir 2 years postfire by the number of successful bark beetle entry holes observed from the ground, which were ranked into classes: 0, 1 to 10, 11 to 50, greater than 50. For their study in the Northern Rockies (Peterson and Arbaugh 1986), insect damage was included as a significant variable with and without crown scorch volume in multivariate discriminant functions that separated dead and live trees. They also presented a predictive logistic regression model with crown scorch volume and insect damage as significant variables, but this model did not fit the data as well as models with crown scorch volume alone or crown scorch volume combined with bark char ratio. In contrast, Peterson and Arbaugh's (1989) similar study of 294 postfire Douglas-fir trees in the Cascade Mountains did not find insect damage as a significant variable in logistic regression models and suggested that regional climate patterns may explain the differences. Another suggestion in regard to the variability of postfire insect influences is that fires may occur after the flight period for adult bark beetles or a population of bark beetles may not be close enough to take advantage of the fire-damaged trees (DeNitto and others 2000).

A direct, lower-bole-only approach to investigate the delayed mortality effects of fire and bark beetle interactions following the 1988 Greater Yellowstone Area wildfires was initiated by several workers (Amman 1991; Amman and Ryan 1991; Rasmussen and others 1996; Ryan and Amman 1994, 1996). Fire damage to the cambium was estimated by visual inspection of the cambium and expressed as percent basal girdling. Insect attack was detected by boring dust and entrance/exit holes; species identification was by removal of small patches of bark. These studies used criterion-based definitions of delayed-fire-effect mortality and insect-attack-induced mortality in an attempt to separate these often confounding postfire mortality causes. Mortality due to complete fire girdling (100 percent basal circumference cambium kill) was attributed to fire, while dead trees with less than 100 percent girdling and infested by bark beetles or borers were attributed to insect mortality. Using these criteria in a survey of 1,012 Douglas-fir in lightly burned-to-unburned areas, they found 19 percent delayed mortality due to fire and 13 percent delayed mortality due to insects (primarily Douglas-fir beetles, *Dendroctonus pseudotsugae*) at 4 years postfire. These studies along with Wallin and others' (2003) experimental approach seem to present the clearest evidence on the interaction of fire and subsequent insect attack for postfire mortality in ponderosa pine and Douglas-fir.

Although tree dbh is not a fire-damage measurement, it is "widely recognized as a factor in resistance to fire damage" (Ryan and others 1988), and thus many studies included dbh as a variable in their analysis of postfire mortality. Cambial resistance to fire damage is directly proportional to bark thickness (Hare 1961; Martin 1965), and larger trees with thicker bark are more resistant to fire damage (Peterson and Arbaugh 1989; Ryan and others 1988; Saveland 1982). Larger trees also have greater mass and therefore greater heat capacity that "provide[s] greater resistance to fire injury" (Peterson and Arbaugh 1989). Most of the studies we reviewed found dbh to be significantly different between live and dead trees, or it was a significant component of predictive mortality models in both Douglas-fir and ponderosa pine (Bevins 1980; Cluck and Smith 2001; Harrington 1993; Regelbrugge and Conard 1993; Ryan and others 1988; Saveland 1982; Saveland and Neuenschwander 1990; Wyant and others 1986). Most models show decreasing mortality with increasing dbh (Bevins 1980; Harrington 1993; Regelbrugge and Conard 1993; Ryan and others 1988; Saveland and Neuenschwander 1990; Wyant and others 1986). The only dissenting evidence on the influence of tree dbh comes from Swezy and Agee (1991) who presented data showing no significant dbh difference between live and dead ponderosa pine in Oregon, from McHugh and Kolb (2003) who showed no significant dbh difference on the Bridger-Knoll wildfire in Arizona, and from Weatherby and others (1994) who showed no significant dbh difference in Douglas-fir 4 years postfire in Idaho. Note that Weatherby and others (1994) did show evidence of a significant difference in ponderosa pine.

From another perspective, basal area and stand density index were shown to be significant predictive variables for Douglas-fir postfire mortality and subsequent Douglas-fir beetle attack in a Wyoming study (Negron and others 1999). These results were part of a study with a broader approach to Douglas-fir beetle-induced mortality but may represent an important factor to consider in future postfire mortality studies.

Roots

Parameters to measure fire damage to root systems were used less frequently in postfire mortality studies than stem and foliage fire damage measurements and were restricted to aboveground observations (table 1). Two ponderosa pine studies directly measured fine root biomass changes due to prescribed fire (Grier 1989; Swezy and Agee 1991) but did not use these measurements to predict postfire mortality. Ground fire intensity (Peterson 1984; Weatherby and others 1994) and ground fire severity (McHugh and Kolb 2003) have been used as qualitative measures of fire damage to fine roots near the soil surface. Peterson's (1984) ground fire intensity and McHugh and Kolb's (2003) ground fire severity referred to ground char classes developed by Ryan (1982b) that are defined as: **unburned** – no visible effect on soil, fire did not reside on the area although some damage may have occurred to aboveground tissues from convective or radiated heat; **light burn** – litter and duff layers scorched or charred, but the duff is not altered over the entire depth; **moderate burn** – litter completely consumed and duff deeply charred or consumed, but the underlying mineral soil not visibly altered; **deep burn** – litter and duff completely consumed and the structure and color of the mineral soil surface are visibly altered. Complete criteria for these classes are in Ryan and Noste (1985).

Ground fire severity (ground char) has been found to be significantly higher under dead trees than live trees following fire in ponderosa pine (Swezy and Agee 1991, n = approx. 1200; McHugh and Kolb 2003, n = 1367). Weatherby and others (1994) also used a quantitative variable, "percent of area under the dripline burned." However, they provided no data or analysis for it or for ground fire severity.

Because Douglas-fir trees frequently have roots in the layer between duff and mineral soil, compared to a deeper rooting habit for ponderosa pine trees (Ryan 1982a), it may be more susceptible to ground fires that consume most or all of the duff. However, Peterson (1984) implied that ground fire intensity was not all that useful in predicting postfire mortality for 302 Douglas-fir trees in that a discriminant analysis of his 11 variable dataset, five of which were fire damage variables, indicated that crown scorch volume and bark char were the most significant variables. His analysis also found that ground fire severity was not one of the top two most discriminant variables for lodgepole pine *(Pinus contorta),* subalpine fir *(Abies lasiocarpa*), or western red cedar *(Thuja plicata)*.

Seasonal Effects

As first noted by Harrington (1993) and confirmed by this review, most papers on postfire mortality deal with either spring/summer wildfires or fall prescribed burns: spring/summer wildfires (Herman 1950, 1954; Lynch 1959; Peterson 1984, 1985; Peterson and Arbaugh 1986, 1989; Weatherby and others 1994); fall prescribed burns (Saveland 1982; Saveland and Neuenschwander 1989, 1990; Wyant and others 1986). A few researchers, such as McHugh and Kolb (2003), have studied fires in different seasons, but interpretations of their data are confounded by the small number of fires and differences among sites, fire severity, and tree dbh, in addition to season. In an experimental burn specifically designed to determine mortality differences between spring, summer, and fall burns, Harrington (1993) followed post-prescribed fire mortality in 526 ponderosa pine trees for 10 years. He found little difference between spring and summer fire mortality, but these growing-season fires had higher mortality than fall (dormant season) fires (n = 18 plots). The most striking differences were in the smaller diameter classes, but these differences disappeared at greater than 30 cm (11.8 inches) dbh. A study on prescribed fire effects on ponderosa pine greater than 22 cm (8.7 inches) dbh in Crater Lake National Park (Swezy and Agee 1991) corroborates Harrington's (1993) findings showing greater mortality in early season burns. In Douglas-fir, Ryan and others (1988) found that season had significance only when combined with crown scorch volume and number of dead cambium quadrants in predicting mortality after a prescribed burn (n = 20 plots) in Montana, but noted that the seasonal effects in that study may have been related to differences in fire behavior.

Two marking guides have incorporated season of fire differences into their recommendations. Wagener's (1961) marking guide for California made slight adjustments for minimum green canopy for ponderosa pine survival between mid- and late-season fires but *not* in Douglas-fir. Dieterich (1979) recommended delaying salvage marking of ponderosa pine trees damaged during growing-season fires until the following growing season if possible, and if not, then both crown scorch and crown consumption standards should be lowered.

Species Comparison

A study on postfire mortality of seven western conifers that included Douglas-fir but not ponderosa pine indicated that "crown injury is not strongly species dependent" (Ryan and Reinhardt 1988). Only two studies included adequate samples of both Douglas-fir and ponderosa pine (Weatherby and others 1994; Wyant and others 1986), and these studies showed little between-species differences in the effectiveness of commonly used fire damage variables to predict postfire mortality. Douglas-fir and ponderosa pine showed no significant differences in crown scorch volume or bole char ratings within alive, fire-killed, and beetle-killed categories after the Lowman wildfire complex in Idaho (Weatherby and others 1994). Similarly, this study showed no between-species differences in average tree dbh for fire-killed trees, but there were apparent between-species differences in postfire mean dbh for both alive and beetle-killed categories. Two studies found that following wildfire, Douglas-fir beetles apparently selected larger dbh trees (Bulaon 2003; Weatherby and others 1994). Wyant and others (1986) used 16 fire scorch, consumption, and char variables to compare species by fire-killed and surviving tree categories. Fifteen of those showed no significant difference between species but clear live/

fire-killed differences. One variable, maximum scorch height, showed no clear differences between species or between live/fire-killed categories.

Summary by Species

Douglas-fir—There have been few attempts to use root damage measurements to explain postfire mortality (table 1). Three indirect measures of root damage on Douglas-fir were used by workers in this review: ground fire severity and burned area under dripline (Weatherby and others 1994) and fire severity as judged by effect on litter and duff (Peterson 1984). Peterson (1984) found that fire severity effects were not among the top three independent variables to predict postfire mortality, and apparently Weatherby and others (1994) did not analyze their root-damage data.

In contrast, all of the independent stem-damage variables on Douglas-fir in table 1 were found to be significant indicators of postfire mortality in one or more studies. Peterson's studies consistently found bark char ratio to be a significant variable, and two of his studies found percent basal scorch to be significant while one did not (Peterson 1984; Peterson and Arbaugh 1986, 1989, respectively). Weatherby and others (1994) also found percent basal scorch (as a component of bole char ratings) to be significantly different between live and fire-killed trees. Ryan and Amman (1994, 1996) described similar effects. Direct measures of cambium condition were also significant when used (Peterson and Arbaugh 1989; Ryan and others 1988). Insect damage was not consistent; two studies found significant bark beetle influence on mortality (Peterson and Arbaugh 1986; Weatherby and others 1994), but a similar study did not (Peterson and Arbaugh 1989). Ryan and Amman (1996) attributed 13 percent of delayed mortality to bark beetles or wood borers 4 years after the 1988 Greater Yellowstone Area fires.

Crown scorch volume was clearly the best crown damage measurement to predict postfire mortality of Douglas-fir (Peterson 1984, 1985; Peterson and Arbaugh 1986, 1989; Ryan and others 1988). Studies that did not use crown scorch volume (Bevins 1980; Wyant and others 1986) found that crown scorch height/length variables were significantly different between live and dead trees. The only study to use crown consumption variables found that consumption also had significant predictive power (Wyant and others 1986). Crown scorch volume and either bark char ratio, percent basal scorch, or number of quadrants with live/dead cambium appear to be the best overall measurements to predict Douglas-fir, postfire mortality.

Ponderosa pine—Three studies apparently collected data on postfire root damage to ponderosa pine (table 1), but only one study analyzed its data (McHugh and Kolb 2003). This study found significant differences in ground char ratings between live and dead trees on three fires: two wildfires and one prescribed burn.

The literature shows two strong trends in the use of stem damage measurements for predicting postfire ponderosa pine mortality. Bole char height, the most frequently used stem fire-damage variable in ponderosa pine (table 1), was found to be significantly different between live and dead trees in three out of four studies. Similarly, two of the three studies using bole char classes found significant differences between live and dead trees (McHugh and Kolb 2003; Weatherby and others 1994). Two older studies lumped cambium injury and crown injury into broad damage classes (Miller and Patterson 1927; Salman 1934). No one used bark char ratio or bark char depth as in several Douglas-fir studies.

All workers who used crown scorch height, crown scorch volume, or crown consumption (table 1) found them to be significant variables in predicting postfire mortality in ponderosa pine. Saveland and Neuenschwander (1990) were the only investigators who compared the efficacy of scorch height versus scorch volume in ponderosa pine, and they found crown scorch volume to be a better predictor as measured by receiver operating characteristic (ROC) curves, which is a method for evaluating the accuracy of diagnostic systems (Swets and others 1979).

One study combined crown scorch and consumption into a total crown damage variable, which was then coupled with insect attack rating (McHugh and others 2003) as the most predictive variables in a logistic regression model. Wyant and others (1986) compared several crown and bole fire-damage variables and ranked crown scorch variables better than foliage consumption and bark char variables as judged by correlation between predicted and observed outcomes.

Management Implications

Our recommendations for measurements to assess postfire damage to trees and to predict mortality include a measurement of tree diameter size, dbh, plus one measure from each of the three plant organs: foliage, stems, and roots. Several studies showed the importance and utility of measuring both foliage and stem damage (McHugh and Kolb 2003; Peterson 1984; Peterson and Arbaugh 1989; Ryan and others 1988; Wyant and others 1986). Foliage damage, along with stem damage, is clearly the easiest, most pragmatic, and most important measurement as shown in practically all of the studies we reviewed. Fine root damage is the most difficult to measure, and no suitable technique for direct measurement is available.

Foliage damage is best measured by estimating percent crown scorch volume, which usually includes crown consumption. As previously noted, it consistently outperforms crown scorch height or length. From this literature review and from field experience, visual estimates to the nearest 5 percent are possible with reasonable accuracy. Consensus estimates from two to three workers guided by Ryan's (1982a) cautionary notes seems the best approach. If crown damage is the only damage measurement used, as some have recommended for salvage-type marking (Cluck and Smith 2001; Saveland and Neuenschwander 1990), then percent crown scorch volume above 80 to 95 percent for ponderosa pine or above 70 to 95 percent for Douglas-fir would indicate probable tree death ($p > 0.80$) within 2 to 3 years. These figures would need to be reduced when combined with high insect attacks (McHugh and others 2003) or other obvious damage to stems and roots (see Peterson 1984), or with drought conditions.

Direct stem damage measurements are limited to techniques that allow observation of cambium tissue via increment borer samples or removal of small pieces of bark, then judging cambium condition visually or by chemical tests. However, these are destructive sampling techniques and are thus usually limited to one sample from each of four quadrants. These should be analyzed as number of live/dead quadrants (categorical data), since conversion to percent implies higher accuracy. For example, one dead quadrant represents a sampling range of 1 to 49 percent bole scorch circumference. The results of studies using this technique show that more than three dead quadrants alone imply probable tree death. However, this technique is best combined with percent crown scorch volume (Peterson and Arbaugh 1989; Ryan and others 1988). These cambium samples should be taken at dbh or at the root crown.

Because direct measures of fine root damage are time and labor intensive, we recommend the use of ground char classes (Ryan 1982b; Ryan and Noste 1985). Further use of these classes will allow researchers to determine their predictive utility. In addition, new techniques for large scale, direct measurement of fine root mass/root damage are needed.

Based on their use in the papers we reviewed, the following are recommended terms for fire damage measurements. A somewhat conceptual definition and/or specific citation is also shown for each term.

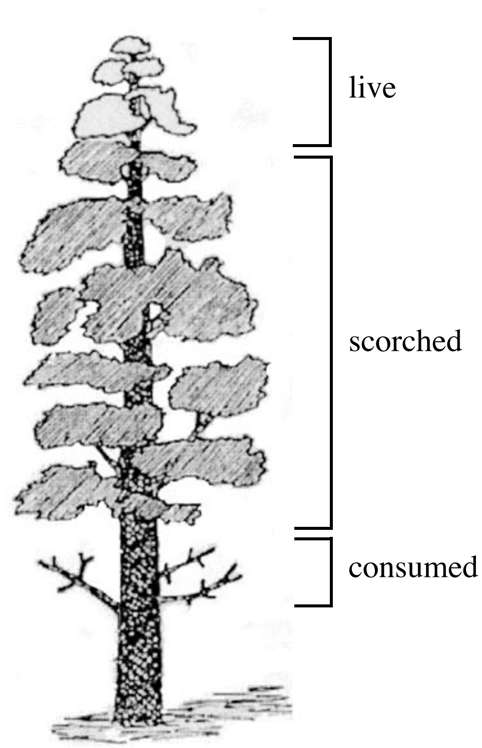

Figure 2—Conceptual drawing of fire damage to foliage and stems. Scorched (fire-killed) foliage and consumed foliage (and buds) are often combined as percent crown scorch volume but may also be separated into separate categories as shown. Figure modified from Miller and Patterson (1927)

- **Percent crown scorch volume:** A visual estimate to the nearest 5 to 10 percent of the proportion of prefire foliage scorched/killed due to fire (fig. 2). It conceptually includes foliage consumption, bud kill, and bud consumption unless specifically excluded in the methods section of a study: in other words, separation of scorch and consumption. See Dieterich (1979) and Miller and Patterson (1927) for photographs of foliage scorch and consumption. Miller and Patterson (1927) also have drawings on their fire injury classes that conceptually show unburned, scorched, and consumed foliage.
- **Crown scorch height:** Maximum height of foliage scorch/kill measured from ground level. Maximum height is inferred unless mean scorch height is specifically mentioned in the methods section of a paper. In that case, the term "average crown scorch height" should be used.
- **Percent crown scorch length:** The proportion of the original crown height with foliage scorch/kill. This would conceptually include foliage consumption, bud kill, and bud consumption unless specifically excluded in the methods section of a paper.

- **Crown consumption:** Percent of crown foliage volume (and buds unless separated) consumed by fire (fig. 2). Use this term when foliage scorch is separated from foliage consumption; see percent crown scorch volume.
- **Bud kill/consumption:** Percent of crown bud volume consumed by fire. Use this term when bud consumption is separated from foliage consumption; see percent crown scorch volume. Note that we know of no studies that have used this measurement.
- **Bole scorch height:** Maximum height of a change in bark color or texture due to fire. This is occasionally expressed as a proportion of tree height, in which case the term should be "relative bole scorch height." This fire damage measurement would conceptually include bark char (a charcoal concept) in lower portions of the same stem unless it is specifically excluded in the methods section of a paper.
- **Bole char height:** Maximum height of charcoal-like bark (see above).
- **Bole damage classes:** See Ryan (1982b) for criteria based on scorch and char.
- **Percent basal girdling:** The proportion of the basal circumference in which cambial tissue is killed. This is measured indirectly by bark scorch/char (see bole scorch height for conceptual differences) or directly by assessing cambial condition (Peterson and Arbaugh 1989; Ryan 1982b; Ryan and Frandsen 1991; Ryan and others 1988).
- **Bark char ratio:** depth of mean bark char as a proportion of original mean bark thickness, which is often calculated from standard equations.
- **Insect damage to bole:** There is no consensus for a definition from the fire mortality literature. We suggest the development of a measure conceptually based on successful/unsuccessful strip attacks and mass attacks (Amman and Cole 1983). This measure should be estimated at the peak of bark beetle populations within a burned area, usually the second growing season postfire.
- **Ground char:** Damage classes based on changes in litter, duff, and soil characteristics due to fire intensity. See Ryan (1982b) and Ryan and Noste (1985) for detailed criteria.

Research Needs

This review points to two broad areas in need of further research to develop accurate measures of postfire mortality: damage to roots and damage to cambium. In both of these areas, direct observation of tissue damage is difficult, and indirect measures have been developed. Measurement of root damage presents the greatest technological challenge and a daunting spatial and temporal sampling problem. Swezy and Agee (1991) measured pre- and postfire fine root masses, but this is time and labor intensive and only works for prescribed fires. As previously noted, Ryan and Noste's (1985) ground char classes may be the only practical solution. Measuring bole and root collar cambium damage, either by fire or insects, is less of a technological problem because visual and chemical techniques exist for assessing tissue condition (Peterson and Arbaugh 1989; Ryan 1982b; Ryan and Frandsen 1991; Ryan and others 1988). The problem is how to assess nondestructively. For insect damage, we suggest research to develop cambial tissue damage measurements conceptually based on successful and unsuccessful postfire strip attacks and mass attacks (Amman and Cole 1983). For fire damage, we suggest research to test the efficacy of Ryan's (1982b) suggestion to stratify cambium sampling by depth of char classes. Cambial sampling with an increment borer at the edge of each depth-of-char class may allow more accurate measurement of percent of circumference girdled by fire. Papers in this review that used percent basal scorch/char (table 1) inferred tissue damage from postfire, external bark characteristics. Workers who sampled cambium condition (table 1) directly, sampled by quadrant. Ryan's suggestion would appear to be more accurate and efficient; thus it needs further evaluation.

This review also revealed the need for more tightly controlled experiments. Differences in the severity of fires, site characteristics, drought history, ranges of tree diameters, and stand densities were confounding factors in a number of the studies we reviewed. There is a need for well-replicated experiments that attempt to standardize site, tree, and fire conditions as much as possible.

Annotated References

Amman, Gene D. 1991. Bark beetle-fire associations in the Greater Yellowstone Area. In: Nodvin, Stephen C.; Waldrop, Thomas A., eds. Fire and the environment: ecological and cultural perspectives, proceedings of an international symposium; 1990 March 20-24; Knoxville, TN. Gen. Tech. Rep. SE-69. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 313-320.

and

Amman, Gene D.; Ryan, Kevin C. 1991. Insect infestation of fire-injured trees in the Greater Yellowstone Area. Res. Note INT-398. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 9 p.

and

Rasmussen, Lynn A.; Amman, Gene D.; Vandygriff, James C.; Oakes, Robert D.; Munson, A. Steven; Gibson, Kenneth E. 1996. Bark beetle and wood borer infestation in the Greater Yellowstone Area during four postfire years. Res. Pap. INT-RP-487. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 10 p.

and

Ryan, Kevin C.; Amman, Gene D. 1994. Interactions between fire-injured trees and insects in the Greater Yellowstone Area. In: Despain, Don G., ed. Plants and their Environments: Proceedings of the First Biennial Scientific Conference on the Greater Yellowstone Ecosystem; 1991 September 16-17; Yellowstone National Park, WY. Denver, CO: U.S. Department of Interior, National Park Service: 259-271.

and

Ryan, Kevin C.; Amman, Gene D. 1996. Bark beetle activity and delayed tree mortality in the Greater Yellowstone Area following the 1988 fires. In: Greenlee, Jason, ed. The ecological Implications of Fire in Greater Yellowstone: Proceedings, Second Biennial Conference on the Greater Yellowstone Ecosystem; 1993 September 19-21; Yellowstone National Park, WY. Fairfield, WA: International Association of Wildland Fire: 151-158.

Annotation: This series of papers contain the results of studies on delayed fire effects and insect induced mortality on Douglas-fir *(P. menziesii),* lodgepole pine *(Pinus contorta),* whitebark pine *(Pinus albicaulis),* Engelmann spruce *(Picea engelmannii),* and subalpine fir *(Abies lasiocarpa)* after the 1988 Greater Yellowstone Area fires. The 1991 and 1994 papers contained preliminary results of studies more fully described in Rasmussen and others (1996) and Ryan and Amman (1996). Only information on Douglas-fir postfire mortality from the 1996 papers is noted here. Mortality was higher for trees with greater than 50 percent crown scorch volume and greater than 75 percent basal girdling. Figure 1 (which is actually switched with figure 3 in the paper) in Ryan and Amman (1996) and figures 12 to 14 in Rasmussen and others (1996) graphically showed increased insect infestation/mortality with increased basal girdling by fire. Delayed mortality from fire effects and insect infestation was 18.5 percent and 12.6 percent (n = 1012 Douglas-fir) respectively in unburned or lightly burned areas of the Greater Yellowstone Area 1988 fire mosaic at 4 years postburn. In these extensive areas, insect infestation, primarily by Douglas-fir beetles, in uninjured trees the first year after the fire was 8 percent, declined to 4 percent by the third year, then increased to 12 percent the fourth year. More intensive sampling at the burned/unburned boundary showed higher Douglas-fir mortality (n = 125); 77 percent were dead due to the combined affects of fire and insects. The major increase in Douglas-fir beetle infestations (38 percent of the sample) occurred the second year postfire and dropped to 3 percent by the fourth year in these boundary areas.

Bevins, Collin, D. 1980. Estimating survival and salvage potential of fire-scarred Douglas-fir. Res. Not. INT-287. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 8 p.

Annotation: This clear, brief historical introduction to the issue of postfire mortality compares the predictive value of dbh, crown scorch height, and percent crown scorch length (not volume) to predict mortality of Douglas-fir 1 year postprescribed fire in west-central Montana. The criterion for determining live/dead was a chemical test for live cambium in four quadrants at dbh, similar to Peterson's protocol (1984). Most papers use live green foliage as the criterion. Both dbh and crown scorch height were significant variables in the logistic regression model to predict survivability. The sample size (n = 176) is a bit small for predicting mortality in eight dbh classes; otherwise the analysis and interpretation are clear. A preliminary salvage marking guide is presented based upon stem dbh and crown scorch height.

Dieterich, John H. 1979. Recovery potential of fire-damaged southwestern ponderosa pine. Res. Not. RM-379. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 8 p.

Annotation: The study results were based on a November wildfire in northern Arizona. This study had a small sample size (n = 25) and an almost anecdotal approach supplemented with photography. All 25 trees selected for the study had greater than 75 percent crown scorch and seven had some crown consumption. Three of seven trees with some consumption actually survived; these had less than 90 percent crown scorch. Most needle drop occurred in the second winter following a fall fire.

Harrington, M. G. 1987. Ponderosa pine mortality from spring, summer, and fall crown scorching. Western Journal of Applied Forestry. 2(1): 14-16.

and

Harrington, M. G. 1993. Predicting *Pinus ponderosa* mortality from dormant season and growing season fire injury. International Journal of Wildland Fire 3(2): 65-72.

Annotation: This experimental paper was based on an understory prescribed fire in an immature ponderosa pine *(P. ponderosa)* stand (n = 526) in southwestern Colorado during three seasons: late spring, midsummer, and autumn. Tree dbh and foliage damage (percent crown scorch length) were important variables in determining ponderosa pine mortality, but note that trees with "boles charred severely enough to cause cambium damage" were excluded from this study. Dbh and percent crown scorch length results agree with many other studies, but the major importance of the paper is its results on seasonal effects based on an experimental, randomized block design. Fall burns had a lower mortality than spring and summer burns; at 5 years and at 10 years, mortality was 12 percent for autumn burns compared to 26 to 30 percent for spring and summer burns. Spring and summer burns caused high mortality in trees less than 10 cm (4 inches) dbh with greater than 50 percent crown scorch length. Crown scorch mortality thresholds for trees greater than 18 cm (7 inches) dbh were at 90 percent for spring-summer burns and over 90 percent for autumn burns. Mortality for late spring and midsummer fires did not differ; therefore spring and summer fire results were grouped into a "growing season" variable that was significantly different from fall, "dormant season" mortality.

Harrington, Michael G.; Hawksworth, Frank G. 1990. Interactions of fire and dwarf mistletoe on mortality of southwestern ponderosa pine. In: Effects of Fire Management of Southwestern Natural Resources, Proceedings of the Symposium; 1988 November 15-17; Tucson, AZ. Gen. Tech. Rep. RM-191. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 234-240.

Annotation: Crown scorch length (by percent classes) and dbh were significant independent variables in logistic regression modeling of ponderosa pine mortality in Grand Canyon National Park 1 year after an August prescribed burn. Amount of scorch was the dominant factor in first-year mortality. The purpose and most interesting part of this study is the focus on dwarf mistletoe interactions with fire mortality. Dwarf mistletoe ratings (DMR) were also included in their logistic regression model at $p = 0.07$, which indicated that higher mistletoe infection ratings tend to have higher average crown scorch length. In the medium scorch classes, tree mortality increased as dwarf mistletoe infection increased. Results also suggest that dwarf mistletoe can be managed with prescribed fire.

Herman, F. R. 1950. Survival of fire-damaged ponderosa pine. Res. Not. SWFRES-RN-119. Tucson, AZ: U.S. Department of Agriculture, Forest Service, Southwestern Forest and Range Experiment Station. 3 p.

and

Herman, F. R. 1954. A guide for marking fire-damaged ponderosa pine in the southwest. Res. Not. RM-13. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 4 p.

Annotation: This study looked at ponderosa pine (*Pinus ponderosa)* mortality 6 years after a wildfire in northern Arizona. The data show: (1) a clear mortality threshold at greater than 60 percent crown scorch length; (2) a light surface fire had little effect on mortality but heavy ground fire or ground plus crown fire had 50 percent mortality at 50 to 60 percent crown scorch length; (3) tree mortality was hastened by red turpentine beetles only during the first year after burning; (4) bark scorch height and nearby burned out stumps had no effect on mortality. A progress report on the same study (Herman 1950) also noted that not all bark beetle infested trees died. Based on these results, the authors offered these guidelines for marking trees to remove: (1) trees with more than 60 percent of the length of live crown scorched by the fire; and (2) trees with 51 to 60 percent of length of live crown scorch if the fire in the vicinity of the tree was a heavy ground or a combination ground and crown fire. Because these guidelines cannot be expected to cover every individual condition, the author also had other suggestions. For example, if the bark at the base of the tree is severely scorched, the tree may be heat girdled. To check this possibility, a few small cuts may be made through the charred bark. Healthy cambium is white and spongy, but heat-destroyed cambium rapidly turns brown and gives off a distinctive sour smell. Complete or nearly complete heat girdling will kill the trees. The tree has a good chance of surviving if it is only partially girdled. In addition, even relatively light damage to “poor vigor” trees may be enough to cause their death. These guidelines correctly identified 95 percent of the trees that survived and 86 percent of those that died.

Lynch, Donald W. 1959. Effects of a wildfire on mortality and growth of young ponderosa pine trees. Res. Not. No. 66. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 8 p.

Annotation: A moderate sized study (n = 200) on 5 to 30 cm (2 to 12 inch) dbh ponderosa pine (*P. ponderosa*) in Washington 1 to 2 years postwildfire. Results show that mortality was directly related to crown injury with a distinct threshold at 80 percent crown scorch after which mortality jumped from 20 to 24 percent to 63 to 100 percent. All trees died whose crowns were 90 percent or more burned. Second-year mortality was restricted to trees smaller than 6 inches dbh except where crown injury had been 80 percent or greater. Virtually all mortality occurred during the first two years. It is not clear whether percent crown scorch was measured by volume or by crown length. No criteria were given for determining dead/live.

McHugh, Charles W.; Kolb, Thomas E. 2003. Ponderosa pine mortality following fire in Northern Arizona. International Journal of Wildland Fire 12:7-22.

and

McHugh, Charles W.; Kolb, Thomas E.; Wilson, Jill L. 2003. Bark beetle attacks on ponderosa pine following fire in Northern Arizona. Environmental Entomology 32: 510-522.

Annotation: These studies had a relatively large number of trees (1,367) from three fires (a spring wildfire, a summer wildfire, and a fall prescribed fire) and make excellent use of definitions and criteria from the published literature on fire damage parameters. The postfire mortality paper found significant differences between live and dead ponderosa pine 3 years postfire for the following fire damage variables: crown scorch volume, total crown damage, bole char height, bole char severity, ground char severity, and insect attack rating. Total crown damage above 70 to 80 percent resulted in a sharp increase in mortality rate. This paper also included two logistic regression mortality models, but the significance level for variables in the models was $p \leq 0.10$ rather than the traditionally accepted level of $p \leq 0.05$. The U-shaped dbh-mortality curve showing increased mortality in larger dbh classes seems counterintuitive and warrants further investigation. Further analysis of this data set showed that both dbh and individual fire characteristics affected mortality in this study (King, McHugh, and Kolb, personal communication).

The bark beetle paper presented data that clearly show an increase in mortality with increasing crown damage by fire at different levels of insect attack. Distinct mortality thresholds are not apparent. Total crown damage and insect attack rating variables were significant components ($p \leq 0.05$) of a logistic regression model that predicted probability of postfire mortality.

Miller, J. M. 1929. Why the western pine beetle follows fire. Forest Worker 5(4): 16-17.

Annotation: This brief description of ponderosa pine mortality after a summer wildfire on the Sierra National Forest in California shows results that are similar to Miller and Patterson's (1927) more extensive paper and also attributed almost all postfire mortality to bark beetles. It ignores the possible delayed effects of fire in a drought year and implicated bark beetles in spite of a statement that "conditions in the fire-damaged trees...were found to be unfavorable for brood development" of western pine beetle. However, Miller's estimates of beetle killed mortality show the highest percentage in the 50 to 75 percent crown scorch category, which qualitatively agrees with Wallin and others' (2003) colonization-attempt data.

Miller, J. M.; Patterson, J. E. 1927. Preliminary studies on the relation of fire injury to bark beetle attack in western yellow pine. Journal of Agricultural Research 34(7): 597-613.

Annotation: This study was based mostly on a fall 1917 wildfire in southern Oregon. Its major strengths are twofold: pre- and postwildfire beetle infestation data, and bark beetle performance after fire. The authors presented 3 years of prewildfire data for number of trees killed, timber volume lost, and western pine beetle *(Dendroctonus brevicomis)* infestation followed by 3 years of postwildfire data. The paper focused mainly on fire injured ponderosa pine *(P. ponderosa)* greater than 25 cm (10 inches) dbh killed by western pine beetle. No mortality rates were given, but they could be calculated from data presented in tables. No criteria were given to determine beetle killed versus delayed-effect fire killed trees, but the strong inference is that if western pine beetles were present, mortality was attributed to western pine beetles. For example, postfire timber cruises placed trees in one of five fire injury classes with clear damage criteria. The criteria for injury class 4 stated that the foliage was burned away, terminal buds were killed, but cambium is still alive. These trees died during the first year postfire, yet mortality is attributed to beetles, in spite of injury, which would seem to preclude survival of most trees with or without beetles. The authors clearly showed that western pine beetles moved (up to 3 miles) from areas surrounding the fire into the burned area during the first postfire year, then moved back into the 1 mile zone surrounding the fire during the second postfire year. Mortality peaked within the burned area during the first postfire year and within the 1 mile zone surrounding the fire during the second postfire year then declined to prefire rates in both areas in subsequent years. Beetles were preferentially attracted to trees with light to moderate fire damage during the first year after the fire. Western pine beetle brood success was low within the fire area when adult population size was relatively high; that is, the burn area may have been a population sink. Conversely, brood success in the area immediately surrounding the fire was high when the adult population was high the second year after the fire.

Peterson, David L. 1985. Crown scorch volume and scorch height: estimates of postfire tree condition. Canadian Journal of Forest Research 15: 596-598.

Annotation: The study compared the efficacy of visual estimates of percent crown scorch volume with calculated crown scorch volume based on canopy shape and average scorch height in four common conifer species of the Northern Rocky Mountains (from Peterson 1984). Visual estimates are markedly more accurate. Calculated scorch volume consistently overestimated volume by 23 to 38 percent except for scorch volumes greater than 75 percent (by definition they would be the same at 100 percent). Peterson recommends the use of crown scorch volume rather than crown scorch height when timber managers need to identify trees most likely to die.

Peterson, David L. 1984. Predicting fire-caused mortality in four Northern Rocky Mountain conifers. In: Proceedings of the 1983 Convention of the Society of American Foresters, New Forests for Changing World; 1983 October 16-20; Portland, OR. Bethesda, MD: The Society of American Foresters: 276-280.

and

Peterson, David L.; Arbaugh, Michael J. 1986. Postfire survival in Douglas-fir and lodgepole pine: comparing the effects of crown and bole damage. Canadian Journal of Forest Research 16: 1175-1179.

Annotation: Peterson (1984) was the first of a series of his papers on Douglas-fir *(Pseudotsuga menziesii)* postfire mortality. This paper clearly shows the effect of combining two variables in predicting survivability. Crown scorch volume is the most predictive variable, alone (survival threshold at greater than 90 percent) and with bark char ratio (survival thresholds at greater than 50 percent crown scorch and greater than 0.3 bark char ratio) and percent basal scorch circumference (survival thresholds at greater than 50 percent crown scorch and greater than 70 percent basal scorch). Discriminant analysis was used to choose the most significant predictive variables, then contingency table results with these variables were shown graphically. The 1984 paper had results for 1 year postfire; results at 2 years postfire are presented in Peterson and Arbaugh (1986). At 2 years postfire, crown scorch volume was again the most important discriminant function variable. Bark thickness, basal scorch, bark char ratio, and insect damage were also significant discriminant function variables. The authors indicate that the best logistic regression model for Douglas-fir, judged by three goodness-of-fit tests, combined crown scorch volume with insect damage. Graphical presentation of contingency table analysis of postfire survival as a function of crown scorch and insect damage showed a major threshold at 90 percent crown scorch regardless of insect damage (according to the authors). We note that the medium-high insect damage categories seem to have strong impacts on mortality in the 50 to 70 percent crown scorch range. The authors caution that these results apply only to late summer wildfires and that strict use of logistic regression models is not recommended. This paper shows judicious use of logistic regression models.

Peterson, David L.; Arbaugh, Michael J. 1989. Estimating postfire of Douglas-fir in the Cascade Range. Canadian Journal of Forest Research 19: 530-533.

Annotation: This paper describes mortality of Douglas-fir (*Pseudotsuga menziesii)* using a design similar to the authors' 1986 study, the main differences being geography and season of burn. This study was conducted in the Cascade Range in Washington and Oregon after late spring wildfires rather than late summer wildfires in the Northern Rockies. The results are similar: crown scorch volume was the first variable selected in stepwise logistic regression followed by bark char ratio, site, live cambium, and bark thickness. Insect damage was not a significant predictive variable in this study as it was in their 1986 study. Two graphs show the predicted survival probabilities for actual live and dead trees, demonstrating that the logistic regression model predictions fit quite well for observed live trees but not for observed dead trees.

Regelbrugge, Jon C.; Conard, Susan G. 1993. Modeling tree mortality following wildfire in *Pinus ponderosa* forests in the central Sierra Nevada of California. International Journal of Wildland Fire 3(3):139-148.

Annotation: This cogent, literate paper is a good review of the pertinent fire and statistical literature. Crown injury variables were not used since damage data were collected only at 2 years postfire. However, their logistic regression models based on dbh and char height and on relative char height provide accurate predictions (83 to 96 percent) of mortality as judged by chi-square (likelihood ratio statistic) and receiver-operating characteristic (ROC) curves. For 1,275 trees in 25 stands, 86 percent of which were ponderosa pine, mortality varied directly with increasing height of stem bark char and inversely with increasing dbh.

Rigolot, E.; Ducrey, M.; Duhoux, F.; Huc, R.; Ryan, K.C. 1994. Effects of fire injury on the physiology and growth of two pine species. In: Proceedings 2nd International Conference on Forest Fire Research, Vol II, D.05.; 1994 November; Coimbra, Portugal: 857-866.

Annotation: A controlled experiment helped determine lethal thresholds of tree injury: crown scorch by propane torch and basal circumference cambium injury by narrow heating belt for Aleppo pine (*Pinus Halepensis*) in France or burning wick for ponderosa pine (*Pinus ponderosa*) in Montana. The intended cambium injury was less than actual by 5 percent. For ponderosa pine, cambium injury needed to be in the greater than 90 percent range to induce mortality, and foliage damage had no effect (n = 36). However, these ponderosa pine were in vigorous condition with a mean dbh of 18.5 cm (7.3 inches).

Ryan, Kevin C. 1982a. Evaluating potential tree mortality from prescribed burning. In: Baumgartner, David M., ed. Site Preparation and Fuels Management on Steep Terrain: Proceedings of a Symposium; 1982 February 15-17; Spokane, WA. Pullman, WA: Washington State University: 167-179.

Annotation: This good review covers types of tissue damage from heat, especially via prescribed fire, and contains a good discussion of the rationale of using various fire damage measurements for postfire mortality studies based on the author's experience. Focus is on duration and intensity of heat generated by prescribed fire and how tree species' characteristics relate to surviving different fire intensities and durations in the general context of prescribed fire behavior.

Ryan, Kevin C. 1982b. Techniques for assessing fire damage to trees. In: Lotan, J. E., ed. Proceedings of the symposium: Fire–its field effects; 1982 October 19-21; Jackson, WY. Missoula, MT: The Intermountain Fire Council; Pierre, SD: The Rocky Mountain Fire Council: 1-11.

and

Ryan, Kevin C.; Noste, Nonan V. 1985. Evaluating prescribed fires. In: Lotan, James E.; Kilgore, Bruce M.; Fischer, W. C.; Mutch, R.W., tech. coords. Proceedings – Symposium and workshop on wilderness fire; 1983 November 15-18; Missoula, MT. Gen. Tech. Rep. INT-182. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 230-238.

Annotation: The 1982 symposium paper discusses the use of several fire damage measurements for foliage, bole, and roots. Qualitative, criterion-based fire damage classes are presented for bole char and root damage (ground char). The 1985 symposium presentation expanded on this by proposing a method for classifying fire severity based on four (now widely used) ground char classes and on five flame length categories. This system thus comprises a two-dimensional (4 x 5) matrix. Detailed criteria are given for the ground char classes. There is also a good discussion of fire severity effects on vegetation. Note that Ryan 1982b has been previously cited in many papers as Ryan 1983 and as Ryan 1982b, but because the symposium proceedings does not have a publication date, the date of the symposium (1982) should be used.

Ryan, Kevin C. 1998. Analysis of the relative value of morphological variables in predicting fire-caused tree mortality. In: Viegas, D.X., ed. Proceedings of the 3rd International Conference on Forest Fire Research and 14th Conference on Fire and Forest Meteorology; Luso, Coimbra - Portugal. Coimbra, Portugal: ADAI - Associacao para o Desenvolvimento da Aerodinamica Industrial: 1511-1526.

Annotation: Postfire mortality is reviewed through a discussion of fire behavior, fire damage measurements, and tree physiological response to fire injury. The author emphasized the shortcomings of previous investigative approaches and techniques as well as the need for a generalized model of postfire tree mortality.

Ryan, Kevin C.; Frandsen, W. H. 1991. Basal injury from smoldering fires in mature *Pinus ponderosa* Laws. International Journal of Wildland Fire 1(2): 107-118.

Annotation: The focus is on duff accumulation beneath ponderosa pine (*Pinus ponderosa)* in a 200-year-old stand in Glacier National Park, Montana, and the physical/biological effect of consumption of the duff under 19 trees following a late summer, low intensity prescribed burn. The emphasis is on mortality of cambium samples, not tree mortality. Only four of the 19 trees were killed from basal injury. The authors present data and discus two opposing fire effects. Large trees tend to resist fire injury/mortality due to thicker bark and larger mass. In contrast, larger trees tend to accumulate more duff, which makes the root crown more susceptible to smoldering fire injury. Duff depth increased with tree diameter, which ranged from 50 to 114 cm (20 to 45 inches) dbh, and decreased with distance from the bole, averaging 18 cm (7 inches) deep at 30 cm (12 inches) from the bole and decreasing to an average of 6 cm (2.4 inches) at 210 cm (83 inches) from the bole. Duff accumulation is also related to fire return frequency. Although this stand had not burned for 69 years, presettlement return intervals ranged from13 to 58 years.

Ryan, Kevin C.; Peterson, David L.; Reinhardt, Elizabeth D. 1988. Modeling long-term fire-caused mortality of Douglas-fir. Forest Science 34(1): 190-199.

Annotation: This paper follows the fate of 166 Douglas-fir *(Pseudotsuga menziesii)* for 8 years after light surface prescribed burns. Of the total 50 percent mortality, 42 percent had occurred by the end of the third year. Logistic regression results show that cambium damage (number of quadrants with dead cambium at 1.4 m (4.6 feet) bole height) is the most important factor in determining mortality, which would be expected for prescribed burns where fire intensity (and thus crown scorch) were somewhat controlled. Crown scorch volume, scorch height, and dbh were also presented in separate logistic regression models. However, tree height and season of burn were not. Percent crown scorch volume was a better predictor of postfire mortality than scorch height. Fall season fires had slightly higher mortality than spring fires, but the authors note that this may be due to fire behavior differences rather than season. Except for tree height, which is strongly correlated with dbh, each of the above variables was also paired with dbh in four additional logistic regression models. In spite of the heavy reliance on analysis by logistic regression, the authors present, for field use, a figure showing the relationship between dbh and crown scorch volume at three levels of mortality probability.

Ryan, Kevin C.; Reinhardt, Elizabeth D. 1988. Predicting postfire mortality of seven western conifers. Canadian Journal of Forest Research 18:1291-1297.

Annotation: Data on 2,356 trees from 43 prescribed fires in Idaho, Montana, Oregon, and Washington were used to model postfire tree mortality. Data were combined for seven species of conifers to develop binary logistic regression models for predicting the probability of mortality. Douglas-fir *(Pseudotsuga* *menziesii)* trees made up 63 percent of the sample in this study. Bark thickness and percent crown scorch were significant factors in logistic regression models; scorch height was not. The authors interpreted model coefficients to indicate that "the contribution of crown injury is not strongly species dependent." No criteria or methods of measurement for crown scorch or bark thickness were given, but references to previous papers in the introduction infer that crown scorch means both foliage and buds. Because data from 43 fires were pooled, data collection methodology is not completely consistent. We would caution that mortality determination was made at 3 years for 1,146 trees and at 7 to 8 years for 1,210 trees and that Ryan and others (1988) found an additional 8 percent mortality from year 3 to year 8. In addition, mortality cause may be difficult to determine after the first 2 to 3 years postfire.

Saveland, James M.; Neuenschwander, Leon F. 1990. A signal detection framework to evaluate models of tree mortality following fire damage. Forest Science 36(1): 66-76.

Annotation: Reviewing mortality predictions for 194 ponderosa pine *(Pinus ponderosa)* following a fall prescribed fire in Idaho, this study's results indicate that percent crown scorch volume is better than dbh plus scorch height to predict mortality. An excellent presentation on Receiver Operating Characteristic (ROC) curves makes clear use of this analysis technique to compare the accuracy of percent crown scorch volume versus dbh/scorch height in predicting postfire mortality of ponderosa pine. There is also a good discussion on the tradeoffs in using probability of mortality values other than 0.50 as the decision criterion to model dead/alive predictions.

Spicer, J. L. 1982. Probability models to predict Douglas-fir seed tree mortality after prescribed burning. Boise, ID: University of Idaho. 44 p. Thesis.

Annotation: Presented are two models for estimating interior Douglas-fir (*Pseudotsuga menziesii var. glauca*) tree mortality as a direct result of prescribed, understory fire in northern Idaho. Of the variables examined, tree height and percent crown scorch were the most accurate in predicting mortality. The models can be used in conjunction with existing fire behavior models and burning guidelines to aid managers in site preparation decisions.

Swezy, D. Michael; Agee, James K. 1991. Prescribed-fire on fine-root and tree mortality in old-growth ponderosa pine. Canadian Journal of Forest Research 21(5): 626-634.

and

Thomas, Terri L.; Agee, James K. 1986. Prescribed fire effects on mixed conifer forest structure at Crater Lake, Oregon. Canadian Journal of Forest Research 16:1082-1087.

Annotation: This study was based on 10 years of prescribed burns in Crater Lake National Park, Oregon, and corroborates Harrington's (1987, 1993) findings that early season (June and July) prescribed burns have higher mortality rates than late season burns (September). Discriminant analysis showed significant differences between live and dead trees for five variables with scorch height and ground char ranking the highest for approximately 1,200 trees greater than 22 cm (8.7 inches) dbh. Dbh itself was not significant. Interesting data from a small sample (n = 9) of old growth ponderosa pine *(Pinus ponderosa)* are presented on litter and duff profiles before and after burns as well as burn soil temperatures and fine root mass changes by depth, root size classes, and total biomass for unburned, raked and burned, and burn only (litter/duff) trees. The 1986 paper contains an analysis of the 4 years postfire for 117 ponderosa pine in the same area as well as for two other species.

Wallin, Kimberly F.; Kolb, Thomas E.; Skov, Kjerstin R.; Wagner, Michael R. 2003. Effects of crown scorch on ponderosa pine resistance to bark beetles. Environmental Entomology 32:652-661.

Annotation: This paper examines the constitutive and induced resin-flow response as well as *Ips* and *Dendroctonus* colonization with and without pheromone attractants on 40 ponderosa pine *(Pinus* *ponderosa)* following a winter/early spring prescribed burn. The trees were in a narrow (25 to 27 cm, 9.8 to 10.6 inch) dbh class and were categorized into four equal crown scorch volume classes. Constitutive (baseline) resin flow was significantly higher in the 0 to 50 percent crown scorch classes, followed by the 50 to 75 percent and then 75 to 100 percent classes. Induced resin flow (in response to mechanical injury) was highest in the 0 to 25 percent crown scorch class, lower in the 25 to 75 percent classes, and highly variable in the 75 to 100 percent class. Only trees with greater than 50 percent crown scorch had colonization attempts by *Ips* and *Dendroctonus*. Colonization was highest in the 50 to 75 percent crown scorch category and tended to increase from June to September. Pheromone attractants increased the number of successful and unsuccessful colonization attempts in all scorch categories. All trees with greater than 75 percent crown scorch with pheromone attractants had bark beetle *(Dendroctonus)* brood signs and were dead at the end of year 2. The 25 to 50 percent crown scorch class trees had no brood signs and were still alive at the end of year 2.

Weatherby, Julie C.; Mocettini, Phil.; Gardner, Brain R. 1994. A biological evaluation of tree survivorship within the Lowman fire boundary, 1989 - 1993. Unpublished report R4-94-06 on file at: U.S. Forest Service, Intermountain Region, Forest Pest Management, Boise, ID. 9 p.

A**nnotation:** This paper is distinctive in separating beetle killed (criterion based) and fire killed ponderosa pine *(Pinus ponderosa)* and Douglas-fir *(Pseudotsuga menziesii)* for both graphic and descriptive analysis. The results are based on a study of 435 trees within the boundaries of the late summer 1989 Lowman Fire complex in Idaho. The literature review section has good insight into beetle-fire interactions in a mortality context. Although no statistical tests were performed, graphic presentation of descriptive statistics show that beetle-killed Douglas-fir had much less crown scorch (40 percent) than fire-killed Douglas-fir (74 percent), while the difference for ponderosa pine was less and had overlapping 95 percent confidence intervals. In a similar comparison, bark char ratings were higher for both species in fire killed versus beetle killed and in fire killed versus alive trees. The test of Reinhardt and Ryan's (1988) logistic model showed 83 percent accuracy with most of the 17 percent error attributable to species-specific insect affects. Tree dbh was vastly different between fire-killed and beetle-killed Douglas-fir but not so for ponderosa pine. This was due to an apparent selection by Douglas-fir beetles *(Dendroctonus pseudotsugae)* for larger trees that were expected to survive based on Reinhardt and Ryan's (1988) model. For ponderosa pine, western pine beetle *(Dendroctonus brevicomis)* tended to attack the same size class that the model predicted would die.

Wyant, James G.; Omi, Philip N.; Laven, Richard D. 1986. Fire induced tree mortality in a Colorado ponderosa pine/Douglas-fir stand. Forest Science 32(1): 49-59.

Annotation: This excellent prescribed fire paper focuses on fall fires in ponderosa pine-Douglas-fir *(Pinus ponderosa-Pseudotsuga menziesii)* forests in Colorado, where the authors used ANOVA results on 19 independent variables to determine entrance into multivariate discriminant function analysis models. Two functions were produced to predict tree mortality the second growing season after fire for both ponderosa pine and Douglas-fir. Function 2—which included crown scorch volume, stem damage on the least impacted quadrant, and dbh—was chosen as the most pragmatic for each species. Scorch height (maximum) was not significant for mortality predictions. Lower bole damage quadrants (downhill and windward) were second ranked predictors behind crown scorch volume quadrants (uphill and windward) for ponderosa pine and Douglas-fir, respectively. The authors note that there was little between-species difference in levels of mortality-inducing injury to stems and foliage. This paper also has a good discussion on the relevance of tree dbh to fire damage resistance.

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