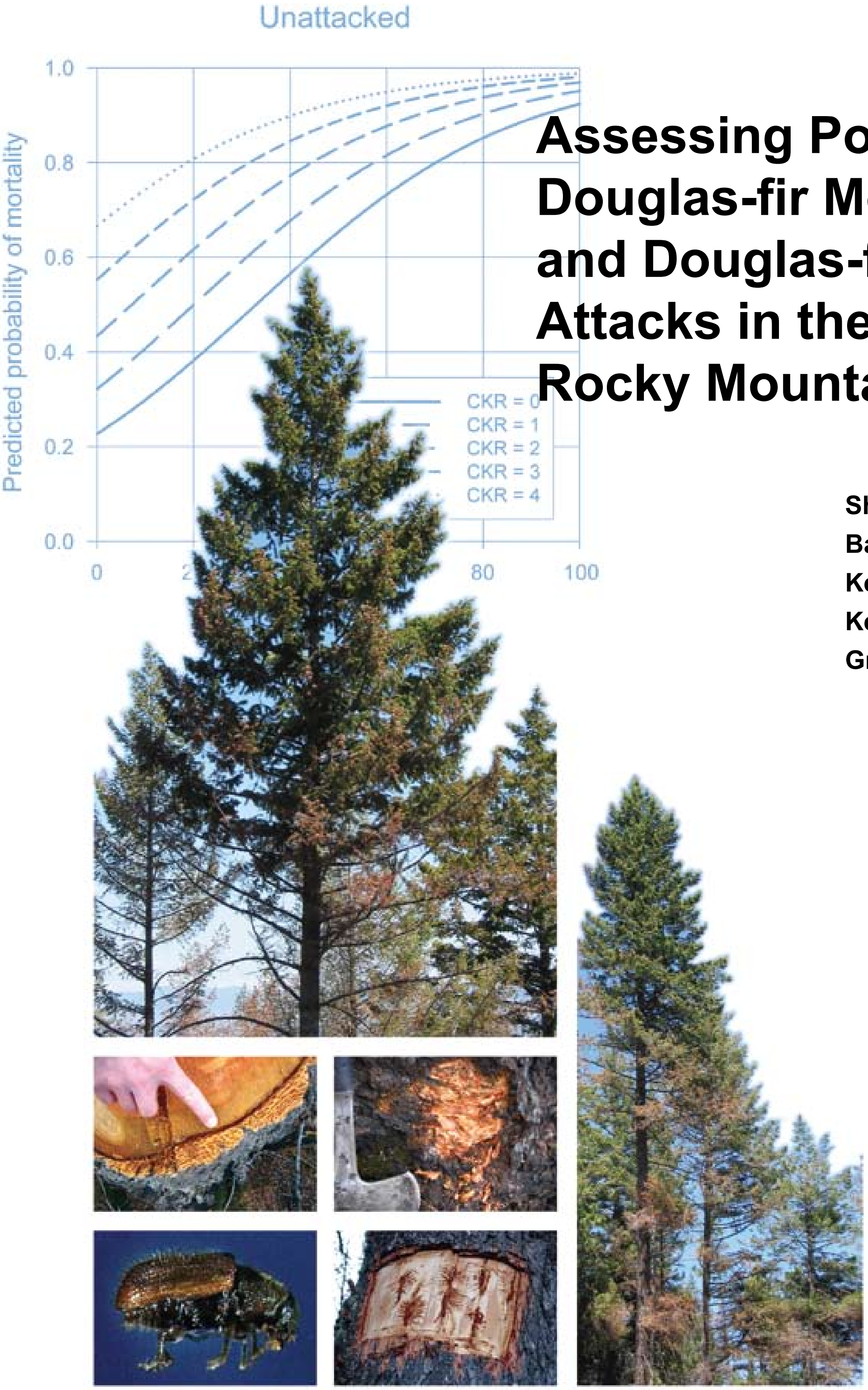

Assessing Post-fire Douglas-fir Mortality and Douglas-fir Beetle Attacks in the Northern Rocky Mountains

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Abstract

Douglas-fir has life history traits that greatly enhance resistance to injury from fire, thereby increasing post-fire survival rates. Tools for predicting the probability of tree mortality following fire are important components of both pre-fire planning and post-fire management efforts. Using data from mixed-severity wildfire in Montana and Wyoming, Hood and Bentz (2007) developed models for predicting the probability of Douglas-fir mortality and Douglas-fir bark beetle attack based on fire injury and stand characteristics. This guide is based on information in Hood and Bentz (2007) and is intended for use in development of post-fire management and prescribed burn plans. Included are descriptions of both models and variables that significantly influence post-fire Douglas-fir mortality and bark beetle attack. A supplemental field guide provides photographs of a range of levels for each fire-related injury and descriptions for measuring each characteristic in the field. Also provided are discussions on how to interpret Douglas-fir mortality and bark beetle attack models for use in management decision-making regarding wild and prescribed fires in the Northern Rocky Mountains.

Key words: photoguide, mortality model, attack model, Douglas-fir, Douglas-fir beetle, salvage

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Introduction

Many coniferous species have life history traits and characteristics that greatly enhance their resistance to injury from fire, thereby increasing post-fire survival rates. Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco), for example, is known for its fire tolerance, in large part, due to thick insulating bark that develops with age and protects the inner cambium from heat injury (Fowler and Sieg 2004; Minore 1979; Ryan 1982a). Mortality following fire, however, depends not only on tree species, but also on type and degree of fire-caused injuries, initial tree vigor, and post-fire environment (Ryan and Amman 1996). These same factors may also influence timing of tree death, which can be delayed as long as 4 years post-fire (Hood and Bentz 2007). Within a few months to a few years following fire, bark and wood boring beetles may preferentially attack trees (Furniss 1965; Hood and Bentz 2007; McHugh and Kolb 2003), and wood deterioration caused by staining, decay pathogens, and/or checking can occur (DeNitto and others 2000; Eglitis 2006). Parker and others (2006) provide an extensive review of interactions between insects and fire (prescribed and wildfire) in coniferous forests of interior western North America. Development of management plans immediately following fire, therefore, can be difficult due to the timing and uncertainty of many interacting factors. Reliable estimates of post-fire Douglas-fir mortality, predicted from field-based characterizations of fire injury, would greatly facilitate informed post-fire management, including salvage, following both mixed-severity wildfires and applications of prescribed fire.

Prediction of fire- and beetle-caused delayed tree mortality is also an important component in the development of prescribed burn plan objectives. Managers must know what fire intensity levels are needed to accomplish mortality related objectives. Also, in adaptive management, a key part to determining if burn objectives were met is installation of monitoring plots. By revisiting prescribed burns and monitoring fire effects, future burn prescriptions can be adjusted to better achieve desired results. To do this, field crews must be able to accurately assess post-fire tree injury and the potential for delayed mortality.

Fire behavior and effects models, such as the First Order Fire Effects Model (FOFEM) (Reinhardt and others 1997) and BehavePlus (Andrews and others 2003), are available for use in predicting post-fire tree mortality (www.fire.org). The tree mortality model in these software packages is based on models developed by Ryan and Reinhardt (1988) and Ryan and Amman (1994). However, this tree mortality model was developed from data for several different tree species. More importantly, this model does not fully account for bark beetle effects on post-fire tree mortality. Douglas-fir bark beetles (*Dendroctonus pseudotsugae* Hopkins Coleoptera: Curculionidae, Scolytine) are highly attracted to fire-injured Douglas-fir and can cause significant tree mortality, apart from fire injuries alone (Cunningham and others 2005; Hood and Bentz 2007). If Douglas-fir beetle populations are a concern following fire, it is important to characterize the fire-related tree injuries most conducive to beetle attack and successful brood production and survival.

Hood and Bentz (2007) developed a model to predict the probability of Douglas-fir mortality and one to predict the probability of Douglas-fir beetle attacks within 4 years post-fire based on data collected from three mixed-severity wildfires in western Montana and Wyoming. The tree mortality model is intended for use on Douglas-fir greater than 5 inches in diameter. Data relating fire-injury to delayed tree mortality and bark beetle attack were used to parameterize the models. The intent of this guide is to facilitate use of these models in post-fire management and prescribed burn planning. We note that ecological and economic constraints make forest management following wildfire a complex task. Our models are meant to be used as part of a multidisciplinary strategy aimed at maximizing benefits to post-fire ecological communities and forest management. Following a brief description of the two models, variables significant in predicting post-fire Douglas-fir mortality and Douglas-fir beetle attack are described. Included is a Supplement with photographs and detailed methodologies for measuring: 1) Douglas-fir beetle attacks and 2) Douglas-fir fire-injury characteristics in the field. Instructions and examples for using the models in post-wildfire management and prescribed burn planning are also provided.

Model Development

We used logistic regression analysis to develop models describing the probability of delayed Douglas-fir mortality and Douglas-fir beetle attack within 4 years post-fire (Hood and Bentz 2007). Models were developed using data collected from three wildfires that burned in 2000 and 2001 in Montana and Wyoming (table 1). We established permanent plots the summer following each fire, and fire injury characteristics and Douglas-fir beetle attacks were quantified on all Douglas-fir ≥ 5 inches in diameter at breast height (DBH) in each plot. The plots were revisited annually during 4 consecutive years to monitor tree mortality and Douglas-fir beetle attacks.

We recorded tree species, status (live or dead), DBH, crown scorch, cambium kill, bark char, ground char, and Douglas-fir beetle attacks for each tree. Trees were considered dead when no green foliage remained in the crown, regardless of beetle attack timing. We determined crown scorch by visually assessing the volume of pre-fire crown that was killed by either direct flame contact or convective heating and therefore, included both scorched and consumed portions of the crown. Bark char and ground char were visually assessed on four sides of each tree as unburned, light, moderate, or deep using the guidelines in Ryan (1982b) and Ryan and Noste (1985). We sampled cambium at ground-line in the center

Table 1. Mean and range of site characteristics of areas burned in three wildfires. Data from these areas were used in development of Douglas-fir mortality and bark beetle attack models (see Hood and Bentz 2007). N represents the number of trees monitored within each burned area.

	Fire		
Site characteristics	**Mussigbrod (n=118)**	**Moose (n=453)**	**Green Knoll (n=218)**
Date	July 2000	August 2001	July 2001
Size (acres)	58,974	70,970	4,513
Location	Beaverhead-Deerlodge N.F., MT	Flathead N.F., MT	Bridger-Teton N.F., WY
Elevation (ft)	6,525 to 6,580	4,600 to 5,840	6,800 to 7,240
Aspect	southwest	south-southwest	southeast
Slope (percent)	38	43 to 51	0 to 14
Stand Density Index of Douglas-fir (SDI_{DF}) (ft^2/ac)	258 (180 to 353)	254 (10 to 399)	87 (73 to 398)
DBH (inches)	11.9 (5.0 to 38.1)	15.0 (5.0 to 41.5)	17.5 (5.0 to 37.7)
Crown volume scorched (percent)	17 (0 to 80)	44 (0 to 100)	34 (0 to 100)
Cambium Kill Rating (CKR)	0.81 (0 to 4)	1.56 (0 to 4)	1.87 (0 to 4)

of each bole quadrant where bark and ground char were also assessed. Using an increment borer, we drilled to the bark-wood interface and visually determined whether the cambium was alive or dead by using the specifications described in Ryan (1982b). The number of quadrants with dead cambium was then summed to create a cambium kill rating (CKR). Douglas-fir beetle-attacked trees were identified based on external bole signs such as reddish-orange boring dust on the lower portion of the tree bole (Schmitz and Gibson 1996; Thier and Weatherby 1991). To correlate fire injury with level of attack, the percent circumference of each tree bole attacked by Douglas-fir beetle (in other words, with visible boring dust) was recorded. See Hood and Bentz (2007) for detailed methodologies of data collection and model development. The significant variables predicting Douglas-fir mortality and bark beetle attacks are explained in further detail in the "Description of Model Variables" section.

Predicting Post-fire Douglas-fir Mortality

Four variables and an interaction effect were significant ($p < 0.05$) in predicting Douglas-fir mortality 4 years post-fire: 1) percent crown volume scorched (scorch), 2) cambium kill rating (CKR), 3) diameter at breast height measured in inches (DBH), 4) Douglas-fir beetle attack level (attacked during first 4 years = 1, unattacked during first 4 years = 0), and 5) the interaction of DBH and attack level. The probability of Douglas-fir mortality (P_m) 4 years post-fire is predicted as:

$$P_m = 1/\left[1 + exp\left(-\begin{pmatrix} -0.8435 + 0.03719(scorch) + 0.4786(CKR) - 0.07658(DBH) \\ -2.2999(attacklevel) + 0.23863(DBH \times attacklevel) \end{pmatrix}\right)\right] \tag{1}$$

The tree mortality model was evaluated using data from 1988 Yellowstone National Park wildfires (Amman and Ryan 1991; Ryan and Amman 1994; Ryan and Amman 1996) and 2002 prescribed burns on University of Montana's Lubrecht Experimental Forest (S. Hood, unpublished data). The model correctly predicted 85 percent of dead trees and 72 percent of surviving trees from the wildfire, and 64 percent of dead trees and 96 percent of surviving trees from the prescribed burns (cutoff $P_m = 0.6$) (Hood and Bentz 2007).

Predicting Post-fire Douglas-fir Beetle Attacks

Four variables and an interaction effect were significant ($p < 0.05$) in predicting the probability of Douglas-fir beetle attack on fire-injured trees within 4 years post-fire: 1) percent crown volume scorched (scorch), 2) cambium kill rating (CKR), 3) DBH (measured in inches), 4) stand density index of Douglas-fir (SDI_{DF}), and 5) interaction of crown scorch, CKR and SDI_{DF}. Probability of Douglas-fir bark beetle attack (P_A) 4 years post-fire is predicted as:

$$P_A = 1/\left[1 + exp\left(-\begin{pmatrix} -5.5625 + 0.0114(scorch) + 0.3031(CKR) + 0.13642(DBH) \\ +0.009463(SDI_{DF}) - 0.000025(scorch \times CKR \times SDI_{DF}) \end{pmatrix}\right)\right] \tag{2}$$

Because Douglas-fir beetles rarely attack small trees (Fettig and others 2007; Furniss 1965; Rasmussen and others 1996; Weatherby and others 2001), the beetle attack model only applies to trees ≥ 9 inches DBH.

The beetle attack model was evaluated using the same data from the Yellowstone wildfires and Lubrecht prescribed burns. Observed bark beetle activity was much higher following the Yellowstone wildfires (71 percent trees attacked) than

Lubrecht prescribed burns (2 percent attacked). The model correctly predicted 85 percent of attacked trees and 48 percent of unattacked trees in the Yellowstone wildfires, and 8 percent of attacked trees and 98 percent of unattacked trees in the prescribed burns (Hood and Bentz 2007).

Description of Model Variables

Percent Crown Volume Scorched

Crown damage from fire is the variable most often used for estimating tree mortality. Many studies have found crown damage to be the best predictor of mortality, and it is also the easiest to observe (Bevins 1980; McHugh and Kolb 2003; Peterson and Arbaugh 1986; Ryan and others 1988; Ryan and Reinhardt 1988; Thies and others 2006; Wagener 1961; Wyant and others 1986). Crown damage can be grouped into two major types- needle scorch and bud kill. Several excellent overviews on the difference between crown scorch and crown kill, and how to detect it, are available (Ryan 1982b; Ryan 1990; Wagener 1961).

Following fire, Douglas-fir crowns may have: 1) green crowns with healthy needles, 2) scorched crowns with brown needles, and 3) blackened crowns with blackened twigs and no needles remaining. Green crown area consists of needles that were not injured by fire. Brown or scorched crown area consists of scorched needles that were killed by super-heated air from the fire, but not direct flame contact. Blackened crown area indicates where flames consumed needles and possibly fine branches. Scorched and blackened needles will soon drop from the crown. Therefore, crown scorch should be evaluated within 1 year post-fire.

The area of green, healthy needles is most always found in the upper most portion of the crown. The green area should not appear to have lost or discolored needles. This area did not receive heat or fire damage.

Scorched needles are brown in color. This area is usually found below the green, unburned area. If needles look "frozen" and brown, they were scorched by fire. This area was exposed to a lethal temperature, which is around 140^{o} F (60^{o} C) for live tissue. Douglas-fir has small, unprotected buds and fine branching structure; therefore, scorched parts of the crown almost always indicate buds are dead (in other words, crown scorch equals crown kill). A limited amount of epicormic sprouting on trees limbs may occur after fire (Hanson and North 2006), but these new twigs comprise only a minimal percentage of pre-fire crown biomass.

The black area is most often toward the bottom of the crown. On a torched tree, the entire crown burned and is black. If twigs are black, the area had actual contact with flames and needles were partially or completely consumed by fire. The percent crown volume scorched variable used in both models is the percentage of crown blackened plus percentage scorched. See the Supplement for detailed methodology on field classification.

Cambium Kill Rating

Cambium injury and bark char are also common variables used to predict tree mortality (Hood and Bentz 2007; Hood and others 2007; McHugh and Kolb 2003; Peterson and Arbaugh 1989; Thies and others 2006; Wyant and others 1986). A tree's bark acts as an insulator to the cambium. Bark thickness varies depending on species, DBH, and age. If lethal heat penetrates through the bark to the cambium layer, it causes cambial kill. Generally, lethal exposure time is 20 minutes per square inch of bark (Ryan 1982a). Because Douglas-fir trees have thick bark, they can be resistant to lethal heating, even with deep bark charring. Therefore, the tree mortality model uses cambium kill rating (CKR) to account for cambium injury instead of bark char. CKR is the number of dead cambium samples based on four samples per tree. CKR, a number between 0 and 4, is calculated by sampling the cambium four times for each tree at groundline and visually determining how many samples are dead. See the Supplement for detailed methodology on field classification.

Visual estimates of bark char are often used as a measure of cambial injury because direct sampling of the cambium is not required (table 2) (Ryan 1982b). However, visual estimates often do not provide a precise measure of cambium death, and therefore will reduce model accuracy (fig. 1) (Hood and Bentz 2007). If visual estimates of cambium condition are used, a subsample of actual cambium condition should be taken. In trees larger than 5 inches DBH, cambium beneath a quadrant with unburned or light bark char is usually alive. Cambium beneath deep bark char is more likely dead. However, direct sampling of the cambium should be

Table 2. Bark char codes and description of bark appearance (adapted from Ryan 1982a).

Bark char code	Bark appearance
Unburned	Not burned
Light	Evidence of light scorching; can still identify species based on bark characteristics; bark is not completely blackened; edges of bark plates charred
Moderate	Bark is uniformly black except possibly some inner fissures; bark characteristics still discernable
Deep	Bark has been burned into, but not necessarily to the wood; outer characteristics are lost

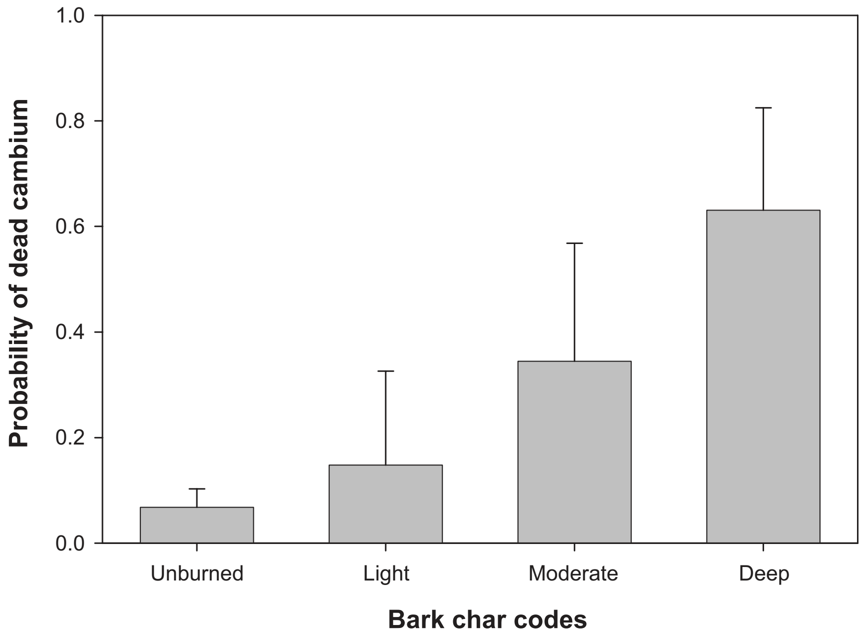


Figure 1. Probability of dead cambium using ocular estimates of Douglas-fir bark char. Bars denote upper 95 percent confidence interval.

conducted if bark char is moderate because moderate bark char does not accurately predict if underlying cambium is live or dead (fig. 1; Hood and others 2007).

DBH

Diameter at breast height (DBH) is a measure of tree circumference taken at 4.5 ft above ground level. DBH is included in the two models in units of inches. Tree size influences post-fire Douglas-fir tree mortality patterns in two ways. First, large trees typically have increased bark thickness, which provides more protection from potential cambium injury during a fire. Also, larger-diameter trees are usually taller and have higher crown base heights than smaller trees. On average, this causes lower crown scorch for any given fire intensity. Therefore, larger trees often have a better chance of surviving a fire than smaller trees due to both reduced crown and bole injury (Agee and Skinner 2005). Second, large trees may also have greater accumulations of duff around the tree base, which can lead to increased basal injury and root injury from long-term smoldering. Large trees may also be less vigorous than small trees, reducing their capability to recover from fire related injuries (McHugh and Kolb 2003). Predicting Douglas-fir post-fire mortality can be further confounded by Douglas-fir bark beetle attacks. Douglas-fir beetles rarely attack trees smaller than 9 inches DBH. Therefore, in burned areas with active Douglas-fir beetle populations, large Douglas-fir trees that could have survived fire-injuries alone are often attacked and killed. Hood and Bentz (2007) estimated Douglas-fir beetle caused an additional 25 percent mortality to fire-injured trees ≥ 9 inches DBH. An interaction effect between DBH and beetle attack level in the tree mortality model is used to include this influence of tree size on Douglas-fir tree mortality. For unattacked trees, the probability of mortality decreases as tree

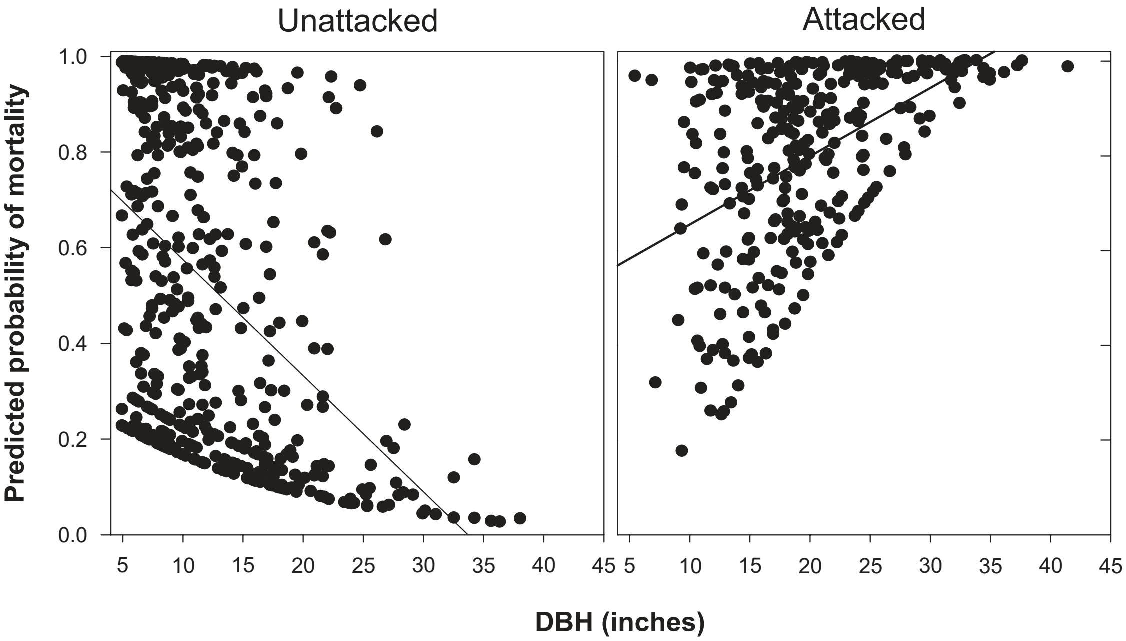


Figure 2. Predicted probability of Douglas-fir mortality (P_m) as a function of Douglas-fir beetle attack status and DBH. P_m decreases with increasing DBH for unattacked trees and increases for attacked trees.

size increases, given the same level of injury. For beetle-attacked trees, the probability of mortality increases as tree size increases, given the same level of injury (fig. 2) (Hood and Bentz 2007).

Douglas-fir Beetle Attack Level

Douglas-fir beetle adults are 0.16 to 0.24 inches long with a black body and reddish-brown wing covers (elytra) (fig. 14, Supplement). The Douglas-fir beetle has consistently been associated with fire-injured Douglas-fir, often attacking larger trees with moderate to high levels of basal bole injury (Furniss 1965; Rasmussen and others 1996; Weatherby and others 2001) and light to moderate levels of crown injury (Cunningham and others 2005; Peterson and Arbaugh 1986; Ryan and Amman 1994; Weatherby and others 2001). Douglas-fir beetles, like other species within the genus *Dendroctonus*, require live or freshly killed phloem for successful brood production and survival (Rudinsky 1962; Schmitz and Gibson 1996). Although downed or stressed trees are often preferred, phloem quality is a determining factor in tree colonization. Beetles also tend to attack trees growing in denser areas with higher stand density indices (Fettig and others 2007; Negron 1998) and trees with a DBH greater than 9 inches (Furniss 1965).

The Douglas-fir beetle lifecycle is univoltine, requiring 1 year for a single generation to be fully completed. New adults emerge from brood trees in late spring or early summer (May through June) depending on temperature (Schmitz and Gibson 1996). Surveys to assess attack status should therefore occur no earlier than July. Following attack of new host trees, a vertical gallery in the phloem is constructed and eggs are deposited in alternating niches on both sides of the parent gallery (fig. 16, Supplement). Following development through four larval instars and a pupal stage, Douglas-fir beetles spend the winter as adults with emergence the following spring/summer.

Hood and Bentz (2007) found no significant differences in fire injuries between mass- and strip-attacked Douglas-fir. Therefore, predictive capabilities of the beetle attack model are binomial (attacked or unattacked), and subsequently, attack level in the mortality model is also binomial. Although unburned trees can typically survive a strip-attack, research suggests the combination of strip-attacks and fire-injuries elevates the probability that a tree will die following fire (Hood and Bentz 2007). If a tree is attacked on >90 percent of the bole circumference, it is considered mass-attacked and will die regardless of fire injuries. Therefore, because the attack-level variable is binomial, the tree mortality model may underpredict mortality for mass-attacked Douglas-fir. In areas where Douglas-fir bark beetle is not a concern, the attack level term essentially drops out of the model and does not influence tree mortality. See the Supplement for detailed methodology on field classification.

Stand Density Index

Stand Density Index of Douglas-fir trees (SDI_{DF}) is a measure of relative stand density that is independent of stand age and site quality (Reineke 1933). The Douglas-fir beetle is known to prefer stands with high host availability and density (Fettig and others 2007; Negron 1998). SDI_{DF} is the same for all Douglas-fir in the stand when computing predicted probability of attack (P_A). SDI_{DF} can be computed from stand plot data as:

(3) $$SDI_{DF} = TPA\left(\frac{DBHq}{10}\right)^{1.605}$$

where:
TPA= Douglas-fir trees ≥ 5 inches DBH per acre
DBHq = quadratic mean diameter in inches

(4) $$\mathrm{DBHq} = \sqrt{\frac{\left(\frac{BasalArea}{TPA}\right)}{0.005454}}$$

(5) $$BasalArea = 0.005454(DBH)^2$$

Using the Tree Mortality Model

The mortality model can be used to develop post-wildfire salvage marking guidelines or as a planning tool when developing prescribed fire burn plans. Detailed examples of how to use the model for these purposes are found in the *Examples of How to Use Tree Mortality and Beetle Attack Models* section.

Using the Tree Mortality Model to Develop Post-fire Marking Guidelines

The tree mortality model estimates a continuous probability (0 to 1) that a Douglas-fir will die within 4 years post-fire. In order to use the model to develop tree marking guidelines following wildfire, a cutoff probability level must be chosen. This cutoff level converts continuous probabilities of mortality into two classes- live and dead. All trees with predicted probability of mortality (P_m) values above the cutoff level are predicted to die and all trees with P_m values below the cutoff level are predicted to live (fig. 3). A classification table is a measure of the accuracy of the model in classifying trees as either live or dead for a range of cutoff levels.

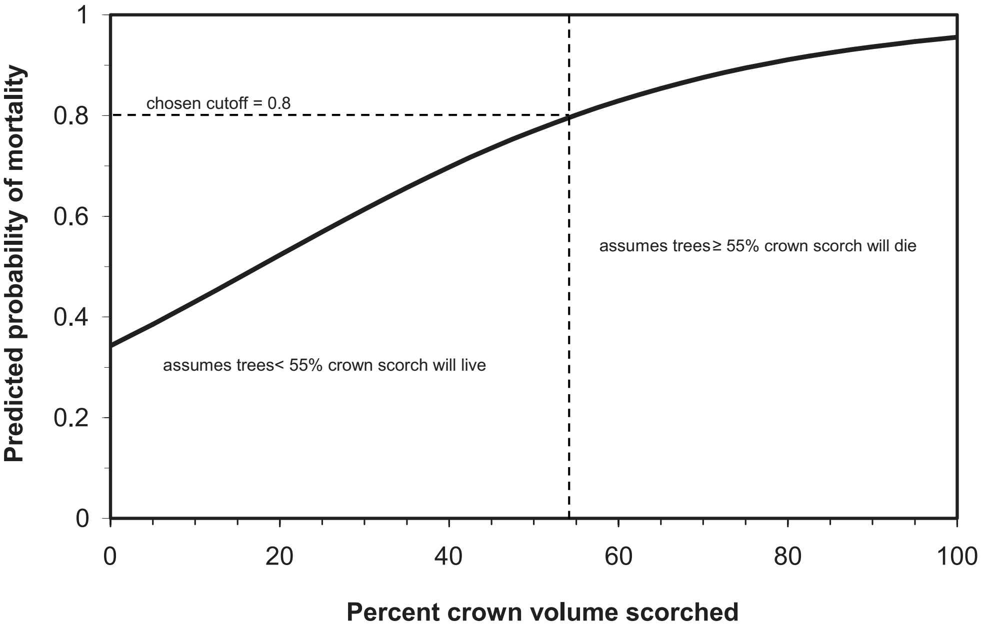


Figure 3. Example using a cutoff level and a probability of mortality curve to predict tree mortality as a function of percent crown volume scorched.

Table 3. Classification table for assessing predictive accuracy of mortality model. Each tree is placed into one of the four categories based on the observed versus predicted event.

		Prediction	
		Live	Dead
Observation	Live	True negative	False positive
	Dead	False negative	True positive

There are four possible outcomes when predicting tree mortality- true negative, true positive, false negative, and false positive (table 3). A classification table summarizes these outcomes by cutoff level to show the percent of trees the model correctly predicted as dead (eq. 6) and as live (eq. 7).

(6) $$\text{Correctly predicted mortality (\%)} = \frac{\text{true positive}}{(\text{false positive} + \text{true positive})} \times 100$$

(7) $$\text{Correctly predicted survival (\%)} = \frac{\text{true negative}}{(\text{false negative} + \text{true negative})} \times 100$$

The goal of classification is to maximize both correctly predicted tree mortality and survival. If the model was 100 percent accurate, all trees predicted to die would actually die and all trees predicted to live would actually live. Of course no model is 100 percent accurate in reality. Therefore, a cutoff level must be chosen that is the best balance of accuracy and management objectives. A very high cutoff of 0.9 may limit the number of false positives (trees predicted to die but actually survive). However, this same cutoff may also leave many dead trees on the landscape because of high false negatives (trees predicted to survive but actually died). Alternatively, a low cutoff level may best capture mortality in the area (few false negatives), but many trees that may have survived the fire would be harvested (many false positives). Thus, low cut-off probabilities favor timber volume removal, whereas high cut-off probabilities favor snag retention. The cutoff level chosen is based on management objectives, number of entries that will be made into the

Table 4. Classification table for the Douglas-fir post-fire mortality model. Shown are P_m, the predicted probability of mortality 4 years post-fire, and the percent of trees the model correctly predicted to die and survive.

	Correctly predicted		
P_m	Total correct (percent)	Mortality (percent)	Survival (percent)
0.1	66.7	65.3	97.1
0.2	74.4	72.4	83.9
0.3	77.1	76.8	77.9
0.4	77.7	79.1	74.5
0.5	77.4	81.3	70.5
0.6	77.9	85.1	68.2
0.7	76.9	89.2	64.5
0.8	73.5	92.3	59.5
0.9	65.9	95.2	52.4

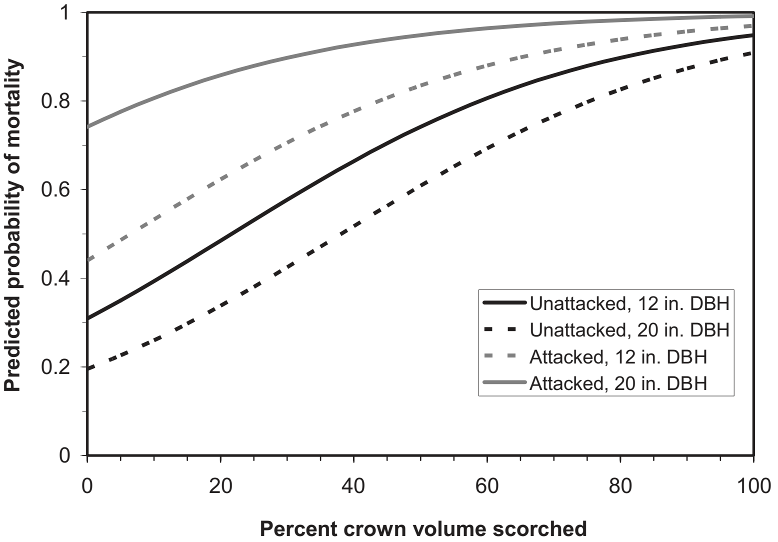


Figure 4. Tree mortality curves showing decreased probability of mortality (P_m) for an unattacked, 20-inch DBH Douglas-fir compared to an unattacked, 12-inch DBH Douglas-fir. The relationship reverses when trees are attacked by Douglas-fir bark beetles.

burned area, other logistical constraints, and the classification table developed from the mortality model (table 4) (Saveland and Neuenschwander 1990).

Once a cutoff level is chosen, mortality curves can be used to determine level of fire injury and tree size necessary to mark a tree for harvest. Mortality curves for a range of tree sizes by attack level are included in Appendix A. By using the classification table in conjunction with mortality curves, marking guidelines can be tailored to best meet management objectives with an associated accuracy level.

Different mortality curves are used for trees attacked by Douglas-fir bark beetles and unattacked trees. For unattacked trees, the P_m decreases as DBH increases. For example, an unattacked 20-inch DBH tree has a lower P_m than an unattacked 12-inch DBH tree with the same fire injury level. However, when a tree is attacked, the P_m increases with DBH. A 20-inch DBH attacked tree has a higher P_m than a 12-inch DBH attacked tree with the same fire injury level (fig. 4).

Mortality curves used in developing marking guidelines can be tailored to specific management and sampling needs. For example, guidelines could be simplified by grouping trees into diameter classes, such as one for trees below 10 inches DBH and one for trees above 10 inches DBH. To reduce sampling time in the field, all trees could be assigned one CKR level and only that specific P_m curve would be used when developing guidelines. Note, however, that model accuracy will be reduced when all model variables are not measured.

Using the Tree Mortality Model for Development of Prescribed Fire Burn Plans

A common objective in a prescribed fire burn plan often includes killing a percentage of understory trees and/or limiting mortality to overstory trees. To use the tree mortality model for this purpose, the predicted probability of mortality is the proportion of trees in the stand predicted to die by diameter class within 4 years post-fire. The classification table displays the accuracy of the model by the chosen

P_m level (table 4). Using the tree mortality model, the percentage of trees predicted to die can be assessed based on a predicted level of crown volume scorched (Albini 1976; Reinhardt and Ryan 1988, 1989; Ryan 1982a, 1990). Subsequently, necessary minimum flame lengths to kill a target percentage of trees, or maximum flame length to prevent a target percentage of trees from dying, can be determined. For example, if a prescribed fire objective is reducing Douglas-fir trees less than 8 inches DBH by 60 percent, then the tree mortality model curves can be used to determine the necessary crown scorch to achieve the objective by selecting a predicted probability of mortality equal to 0.6. The tree mortality model may also aid in identifying opposing management objectives that cannot be met with one treatment.

Using the Douglas-fir Beetle Attack Model

The beetle attack model is intended to be used in conjunction with the tree mortality model in burned areas. This model describes the probability of Douglas-fir beetle attack based on fire injury level, stand conditions, and tree size. Other models are available for determining susceptibility of trees within non-burned stands (Negron 1998; Negron and others 1999; Shore and others 1999). Beetle-infested trees are vital to the success of many woodpecker species following fire (Dixon and Saab 2000; Hutto 2006; Nappi and others 2003), including several species designated by federal and state agencies as management indicator and sensitive species (Russell and others 2006). Therefore, our beetle attack model may also be used for designating leave-trees for post-fire wildlife habitat. Detailed examples of how to use the model are described in the *Examples of How to Use Tree Mortality and Beetle Attack Models* section.

Using the Beetle Attack Model to Develop Post-fire Marking Guidelines

Often, Douglas-fir beetle attack levels are unknown when marking trees post-fire. Either marking occurs before the current year's beetle flight or attacks occur 2 to 4 years following a fire. In these cases, the beetle attack model can be used to estimate attack level (attacked or unattacked) for subsequent use in the tree mortality model.

The beetle attack model is applied in a similar fashion as the mortality model. A continuous probability of attack is estimated between 0 and 1, and an appropriate cutoff level must be chosen to classify trees into an attack level (table 5). All trees with P_A values above the cutoff level are predicted to be attacked. All trees with P_A values below the cutoff level are predicted to be unattacked.

Included in the beetle attack model is an interaction term including scorch, CKR, and $SDI_{DF.}$ Larger trees and trees in denser areas of Douglas-fir have a higher probability of being attacked (fig. 5). While beetles are often attracted to stressed, large trees in dense areas (Fettig and others 2007), there must also be enough living phloem in the tree for beetles to successfully reproduce and for broods to survive. Our data suggest that beetles do not preferentially attack trees with both high levels of crown scorch and cambium injury. Instead, some intermediate level of fire-induced injury provides enough physiological stress for the tree to be overcome by Douglas-fir beetles and for phloem quality to be sufficient for successful brood production.

Table 5. Classification table for the post-fire Douglas-fir beetle attack model. Shown are P_A, the predicted probability of beetle-attack within 4 years post-fire, and the percent of trees the model correctly predicted to be attacked and unattacked.

	Correctly predicted		
P_A	**Total correct (percent)**	**Attacked (percent)**	**Unattacked (percent)**
0.1	53.4	51.5	100
0.2	61.8	57.4	76.8
0.3	68.1	64.2	74.6
0.4	67.1	66.8	67.4
0.5	64.8	69.9	61.9
0.6	64.5	78.5	59.9
0.7	62.3	86.0	57.6
0.8	55.9	88.4	53.4
0.9	52.1	85.7	51.3

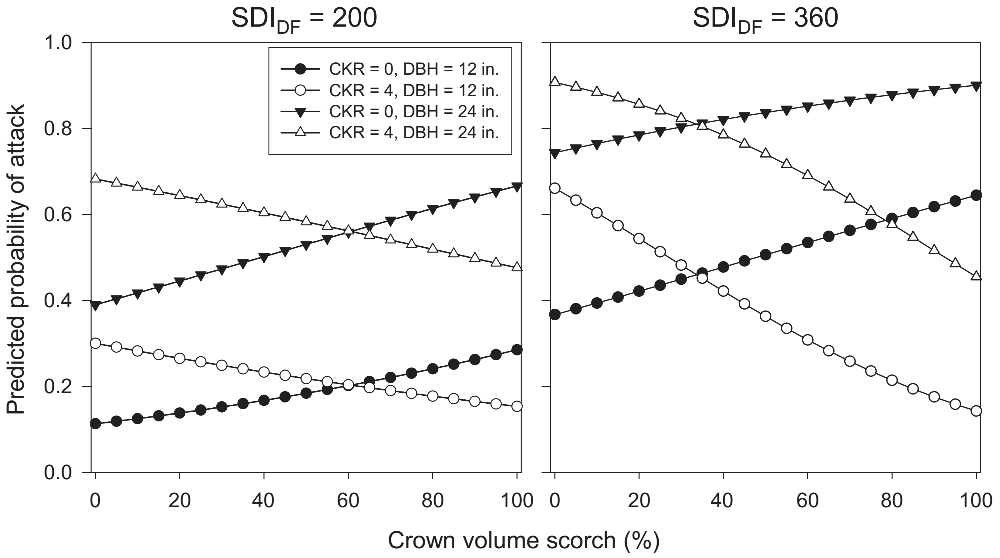


Figure 5. Predicted probability of Douglas-fir beetle attack as a function of crown volume scorched, DBH, Douglas-fir stand density index (SDI$_{DF}$), and cambium kill rating (CKR). For simplicity, results for two levels of SDI$_{DF}$, DBH, and CKR are shown. Other CKR values fall between the two lines.

Using the Beetle Attack Model for Development of Prescribed Fire Burn Plans

In areas with known Douglas-fir beetle activity, the beetle attack model can also be used when developing prescribed fire burn plans. The probability of beetle attack can be estimated from observed Douglas-fir SDI and DBH measurements and expected fire injury levels. Based on this assessment, the accepted mortality level of larger trees may need to be increased in anticipation that some trees will be attacked by Douglas-fir beetle. For example, say expected mortality of Douglas-fir larger than 16 inches DBH is less than 10 percent based on anticipated fire behavior in a planned prescribed burn. However, there is some Douglas-fir beetle activity in the area. Therefore, the accepted level of mortality stated in the prescribed fire burn plan should be raised in order to account for additional mortality that the Douglas-fir beetle may cause by attacking fire injured trees.

Examples of How to Use Tree Mortality and Beetle Attack Models

The following exercises are only intended to illustrate how tree mortality and Douglas-fir beetle attack models are applied in making pre- and post-fire land management decisions. These are simplified examples. They will differ from actual land management plans with changes in management objectives and goals. When using the mortality curves to determine the levels of fire-related injury that will likely cause tree mortality, it is important to remember that the curves represent mean values. The upper and lower 95 percent confidence intervals around this mean can vary considerably, up to ± 20 percent crown scorch.

Exercise 1: Developing a post-fire salvage marking guideline

- *State the management objectives*. For this example, the main objective is a salvage operation to recover merchantable wood fiber from a burned area. Protecting soil productivity and retaining forest structural elements such as snags, downed wood, and living trees are also important objectives.
- *Identify constraints to the salvage operation and quantify nearby Douglas-fir beetle activity*. To limit soil compaction and maintain soil productivity, only one entry into the stand is allowed. To ensure adequate retention of snags for wildlife habitat, no trees over 20 inches DBH will be harvested. Based on ground reconnaissance and Aerial Detection Surveys (USDA Forest Service, Forest Health Protection, http://www.fs.fed.us/r1-r4/spf/fhp/aerial/gisdata), Douglas-fir bark beetle activity in the area is identified as high. Tree marking will not occur until after beetle flight.
- *Choose a cutoff level from the mortality model classification table* (table 4). Based on the first objective of maximizing merchantable fiber and because only one stand entry is allowed, you decide a lower cutoff level is more appropriate. No trees over 20 inches DBH will be harvested, thereby providing snag retention for wildlife habitat. Additionally, due to associated model error, some trees predicted to survive will eventually die providing additional snags on the landscape. You decide to choose a cutoff level of 0.6.
- *Use model derived mortality curves to identify fire-related injury levels of trees that will be marked for harvest*. Using the chosen cutoff level of 0.6, draw horizontal cutoff lines across the mortality curves where the y-axis equals 0.6 for the range of tree sizes in the stand (10 and 15 inches DBH) (fig. 6). Next, draw vertical lines at the intersections of the cutoff lines and CKR curves (fig. 7). All trees with a crown scorch greater than or equal to the value associated with each CKR have a high probability of dying. For example, all 15-inch DBH unattacked trees with CKR = 0 and crown scorch ≥ 65 percent are predicted to die within 4 years post-fire (fig. 7).
- *Create salvage marking guidelines*. Using the lines drawn on the mortality curves (fig. 7), group trees based on fire-injury, attack level, and tree size. These groupings are based on differences in the mortality and attack curves and other factors such as experience level of marking crews, time constraints, etc. For example, differences in predicted mortality curves for 10-inch DBH attacked and unattacked trees are negligible. Therefore, these trees can be grouped into one class. Next, trees with a CKR value ≥ 2 are placed in one group, and those with a CKR value <2 in another group. Based on these two groups, trees with a CKR

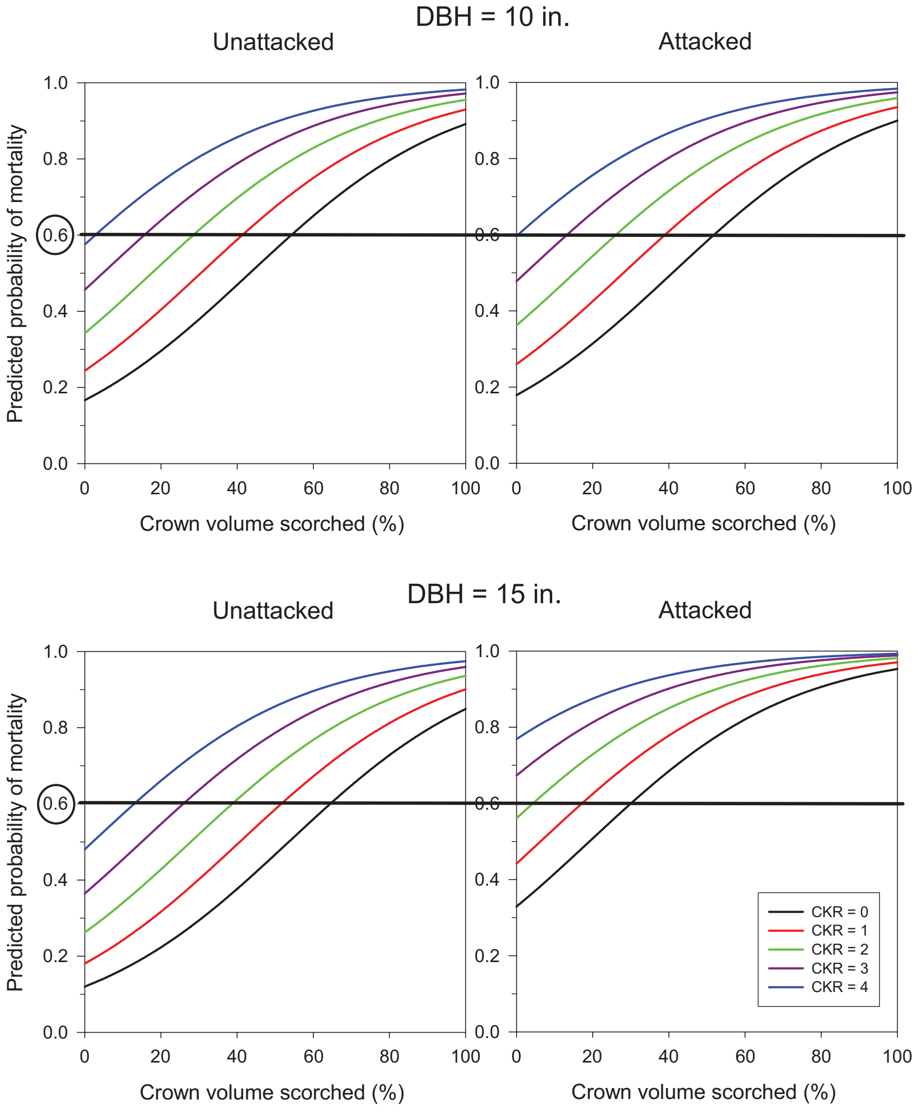


Figure 6. Exercise 1—Model-derived tree mortality curves for 10- and 15-inch DBH trees. Horizontal lines represent cutoff probability level = 0.6. CKR = cambium kill rating.

value ≥ 2 will be marked for cutting if crown scorch is > 30 percent. Trees with CKR < 2 must have crown scorch > 55 percent to warrant cutting. Trees ≥ 15 in DBH but < 20 inches DBH, are grouped into attacked and unattacked classes. Based on the cutoff level = 0.6, all attacked trees with crown scorch > 30 percent will be marked. Unattacked trees with CKR values ≥ 2 and crown scorch > 40 percent or CKR values < 2 and crown scorch > 65 percent will be marked. No trees > 20 inches DBH will be marked. Now create a simplified marking guideline that summarizes these decisions for field marking crews (table 6).

Exercise 2: Developing a prescribed fire burn plan to meet mortality associated objectives

- *State the mortality related management objectives of the prescribed burn.* In this example, the objectives are to reduce ladder fuels and in-growth trees by 70 percent. The majority of the trees in this category are Douglas-fir. Average tree height is 24 ft, with a crown ratio of 0.8. Average DBH is 5.4 inches.
- *Use model-derived mortality curves to determine the minimum scorch necessary to achieve mortality objective.* Draw a horizontal cutoff line on the mortality curve for 5-inch DBH trees where the y-axis equals 0.7 (fig. 8).

Figure 7. Exercise 1—Model-derived mortality curves for 10- and 15-inch DBH trees. Crown volume scorched values associated with each cambium kill rating (CKR) for a cutoff level = 0.6.

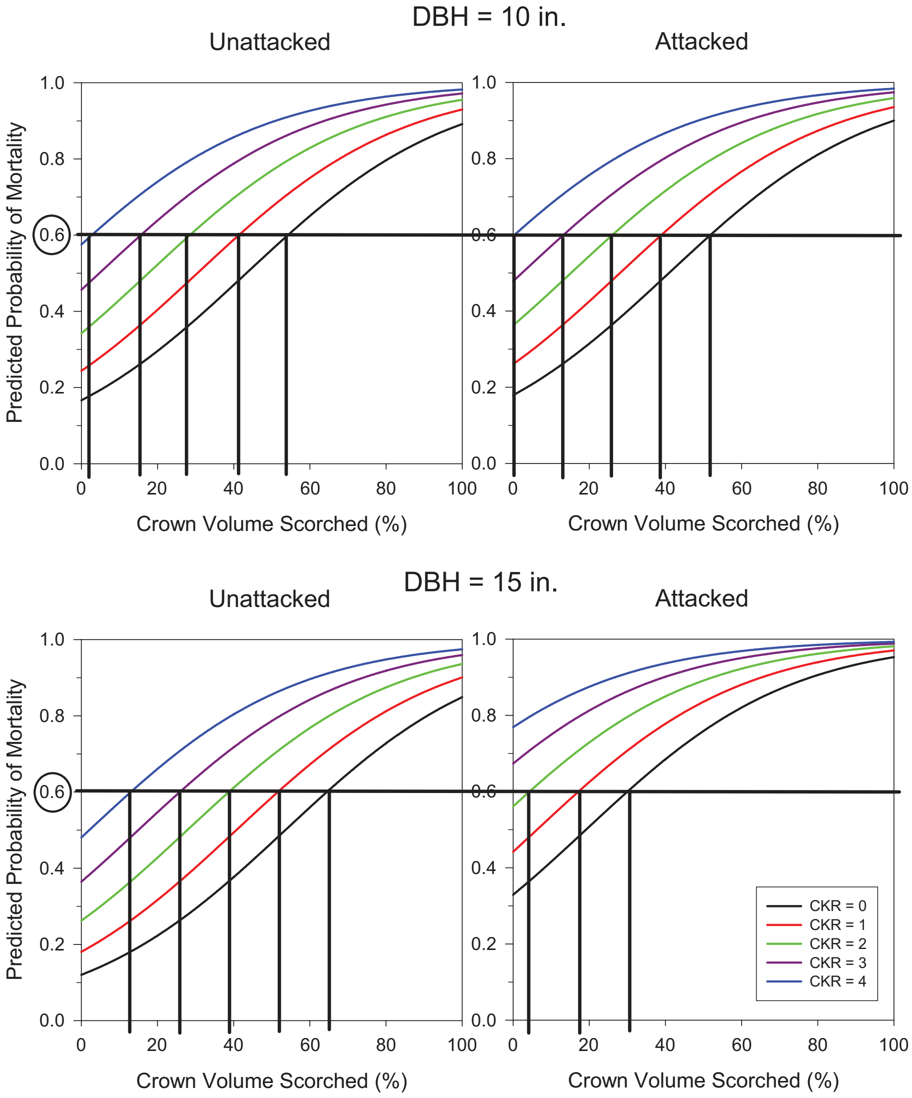
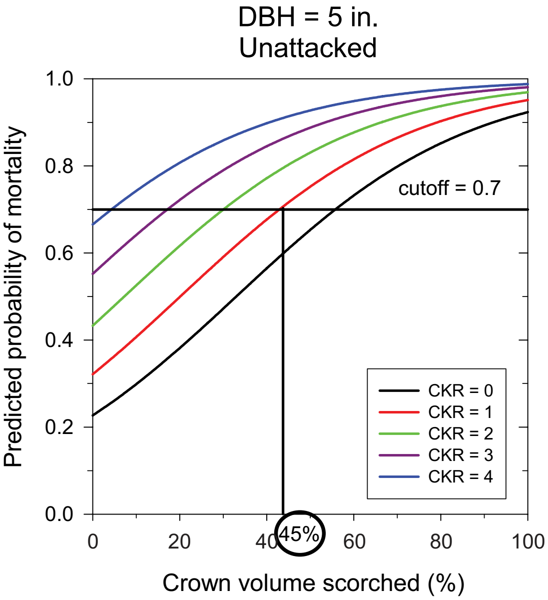


Table 6. Example marking guideline developed from Appendix A, Exercise 1.

DBH	Mark to cut if:
<15 inches	CKR ≥ 2 and crown scorch > 30 percent CKR < 2 and crown scorch > 55 percent
15 to 20 inches	
Attacked:	Crown scorch > 30 percent
Unattacked:	CKR ≥ 2 and crown scorch > 40 percent CKR < 2 and crown scorch > 65 percent
20+ inches	DO NOT MARK

Choose CKR value(s) that will likely occur during the burn. Burning is planned for the spring, under higher moisture conditions, so you choose CKR = 1. Draw a vertical line where the cutoff line intersects with the CKR = 1 curve (fig. 8). Model predicted mortality suggests that 45 percent crown scorch is necessary to kill 70 percent of the Douglas-fir in-growth trees in the unit.

Figure 8. Exercise 2—Model-derived tree mortality curve for 5-inch DBH trees. Based on the tree mortality model, prescribed burn plans should target 45 percent crown scorch to remove 70 percent of 5-inch DBH trees. CKR = cambium kill rating.



- *Determine necessary flame length to achieve desired level of crown scorch*. Flame lengths can be determined using fire behavior and effects models or the nomographs in Albini (1976) and Reinhardt and Ryan (1988). We used BehavePlus (www.fire.org) for this exercise. Using the mortality and crown scorch modules in BehavePlus, enter the expected weather conditions, tree information, and range of flame lengths. BehavePlus predicts 27 percent crown volume scorch when flame lengths are 2 ft, and 77 percent when flame lengths are 3 ft when burning on a 77°F day with 2 mph mid-flame windspeed. Therefore, to kill approximately 70 percent of the in-growth Douglas-fir, flame lengths between 2 and 3 feet are required.

Exercise 3: Using the Douglas-fir beetle attack model and the tree mortality model to develop a salvage marking guideline

In this example, management objectives are similar to Exercise 1, but tree marking will occur before beetle flight and multiple stand entries are possible. Therefore, the beetle attack model is used to develop fire injury level guidelines for trees predicted to have a high probability of beetle attack.

- *State the management objectives*. For this example, the main objective is a salvage operation to recover merchantable wood fiber from a burned area. Retaining forest structural elements, such as snags, downed wood, and living trees for a seed source, are also important objectives.
- *Identify constraints to the salvage operation and quantify nearby Douglas-fir beetle activity*. Up to two stand entries are feasible. To ensure adequate retention of snags for wildlife habitat, no trees over 25 inches DBH will be harvested. Ground reconnaissance and Aerial Detection Surveys suggest that Douglas-fir bark beetle activity in the area is high. Due to other constraints, tree marking for the first harvest will occur before beetle flight has ended (in other words, prior to ~ mid July). A second stand entry to harvest additional dead or attacked trees could occur later if necessary. Based on stand data, you calculate the average $SDI_{DF} = 350$.

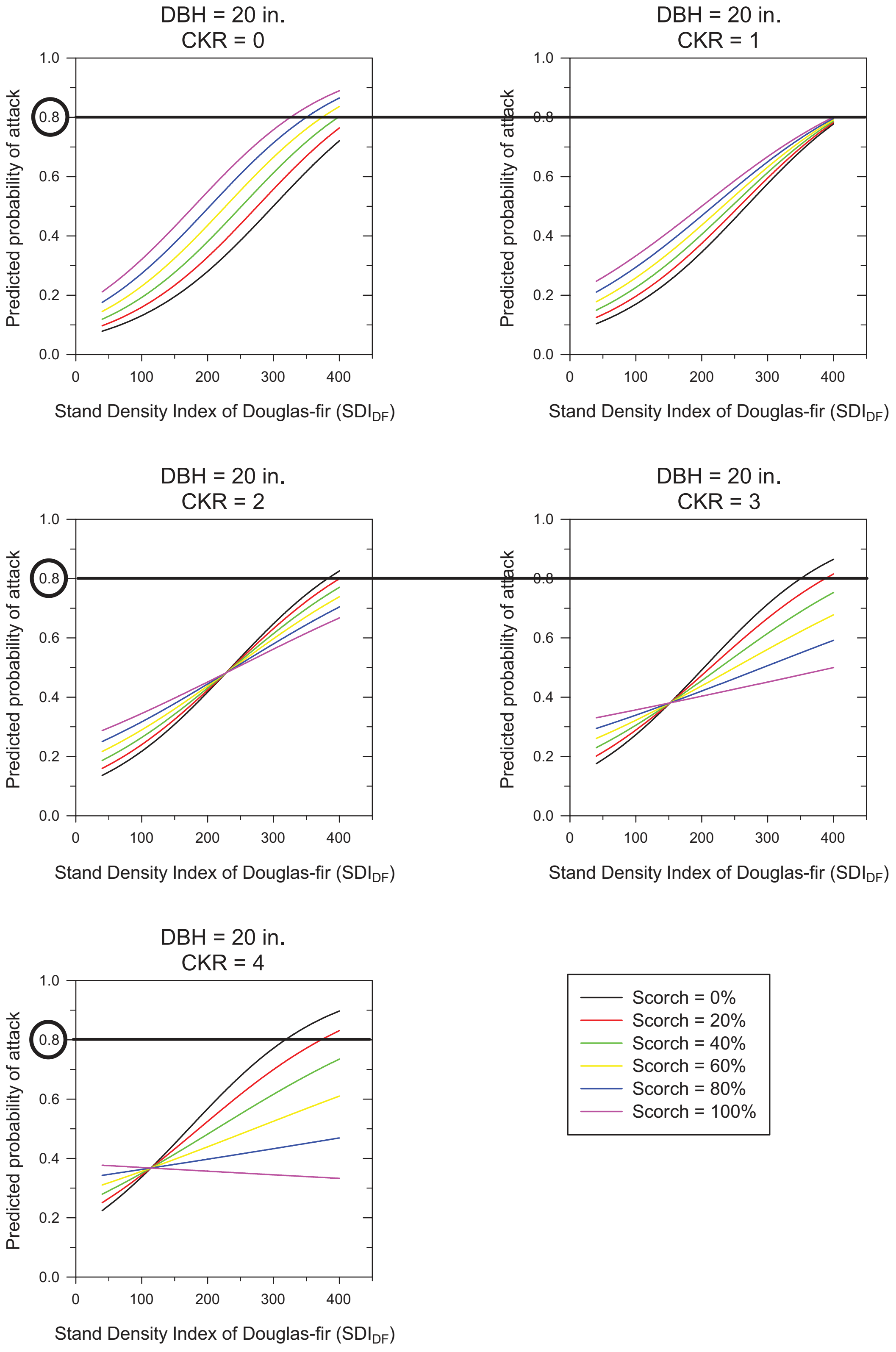


Figure 9. Exercise 3—Curves are derived from the beetle attack model using cambium kill rating (CKR), percent crown volume scorched (Scorch), and Douglas-fir Stand Density Index. Horizontal lines show probability of beetle attack cutoff level equal to 0.8.

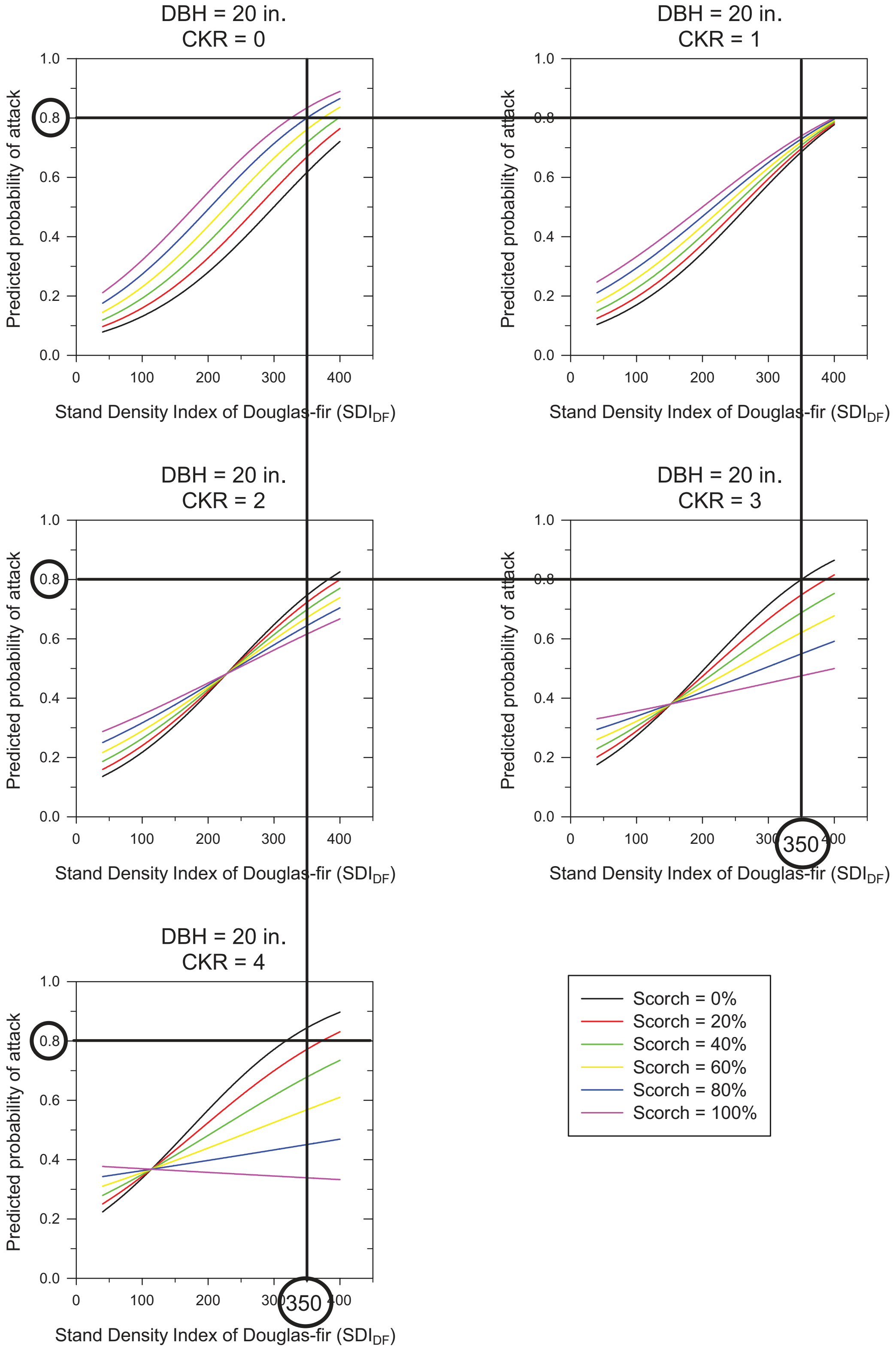


Figure 10. Exercise 3—Curves are derived from the beetle attack model using cambium kill rating (CKR), percent crown volume scorched (Scorch), and Douglas-fir Stand Density Index (SDI_{DF}). Horizontal lines show probability of beetle attack cutoff level equal to 0.8. In this exercise, $SDI_{DF} = 350$. Therefore, all trees with $P_A \geq 0.8$ and $SDI_{DF} = 350$ have a high probability of being attacked.

Table 7. Example attack guideline developed from Appendix A, exercise 3.

DBH	**Attack Level**
<15 inches	Unattacked
15 – 25 inches	Attacked if: CKR = 0 and crown scorch > 80 percent CKR = 3, 4 and crown scorch < 20 percent

- *Choose a cutoff level from the beetle attack model classification table* (table 5). Because a second stand entry is possible, a high cutoff level is chosen to increase the accuracy of correctly predicted attacked trees. Many trees in the unit that are susceptible to bark beetle attacks may remain in the unit, but could be removed in a second entry. A cutoff level $P_A = 0.8$ is chosen.
- *Use model-derived attack curves to estimate fire injury levels most attractive to Douglas-fir beetles*. Draw cutoff lines on the attack curve graphs for 10-, 15-, and 20-inch DBH trees (fig. 9, only DBH=20 inches is shown). Next, draw vertical lines at the intersection of cutoff lines and $SDI_{DF} = 350$ (fig. 10). All trees with $P_A \geq 0.8$ and $SDI_{DF} \geq 350$ have a high probability of being attacked.
- *Create fire injury level guidelines for trees with a high beetle attack probability*. Predicted beetle attack probability for trees with DBH ≤15 inches are less than the cutoff level, $P_A = 0.8$. Therefore, all trees ≤ 15 inches DBH are assumed unattacked. When CKR = 0, all trees with crown scorch ≥ 80 percent are above the cutoff line. Trees with CKR ≥ 3 and scorch ≤ 10 percent are also above the cutoff line. Based on these values, create a beetle attack guideline (table 7).
- The predicted attack levels are then used in conjunction with model-derived mortality curves to determine marking guidelines as described in Exercise 1.

Conclusions

Models developed by Hood and Bentz (2007) predict Douglas-fir mortality and Douglas-fir beetle attacks within 4 years post-fire in areas dominated by Douglas-fir in the Northern Rocky mountains. This guide, in conjunction with the field guide supplement, describes field-data collection methods and use of the models in developing post-fire management and prescribed burn plans. Informed estimates of tree mortality probability will aid management decision making during post-fire management and prescribed burning efforts.

It is important to consider the multi-faceted ecological and economic aspects of post-fire forest restoration efforts in management plans. Our models are intended as one component of the planning process in Douglas-fir forests, and managers should augment their decision criteria with information on many factors, including location of population centers of Douglas-fir bark beetles, localized environmental and tree physiological factors, overall stand health and condition, and objectives for post-fire ecological communities such as snag retention. Crown and mixed-severity fire events are important and natural components of western forest fire regimes (Arno 2000; Hessburg and Agee 2003; McIver and Starr 2000; Schoennagel and others 2004). Post-fire ecological communities are significant elements of the dynamic forest development process and include biological legacies such as standing snags (Beschta and others 2004; Hutto 2006; Spies and others 1988). Retention of dead standing wood following fire benefits many wildlife species, in particular, cavity nesting birds (Russell and others 2006; Saab and Dudley 1998), and forest management plans specifically call for snag retention across burned landscapes.

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Appendix A: Mortality Curves for a Range of Tree Sizes by Attack Level

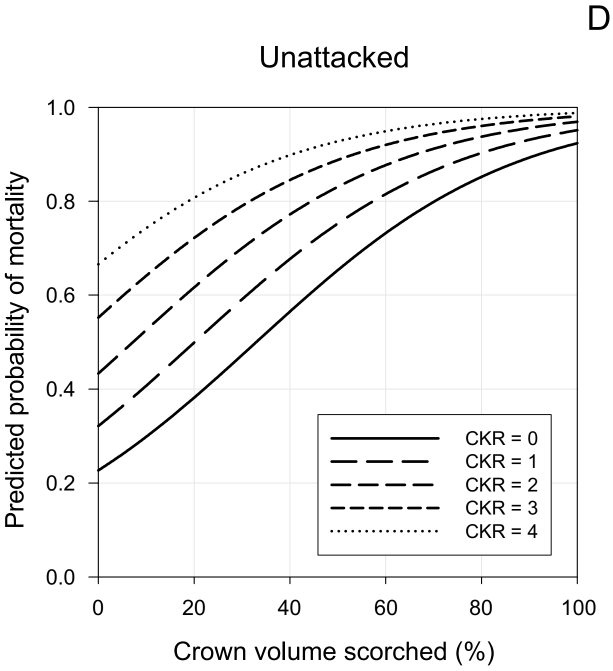


Figure A-1. Predicted probability of mortality curves by Cambium Kill Rating (CKR) and attack status for 5-inch DBH trees.

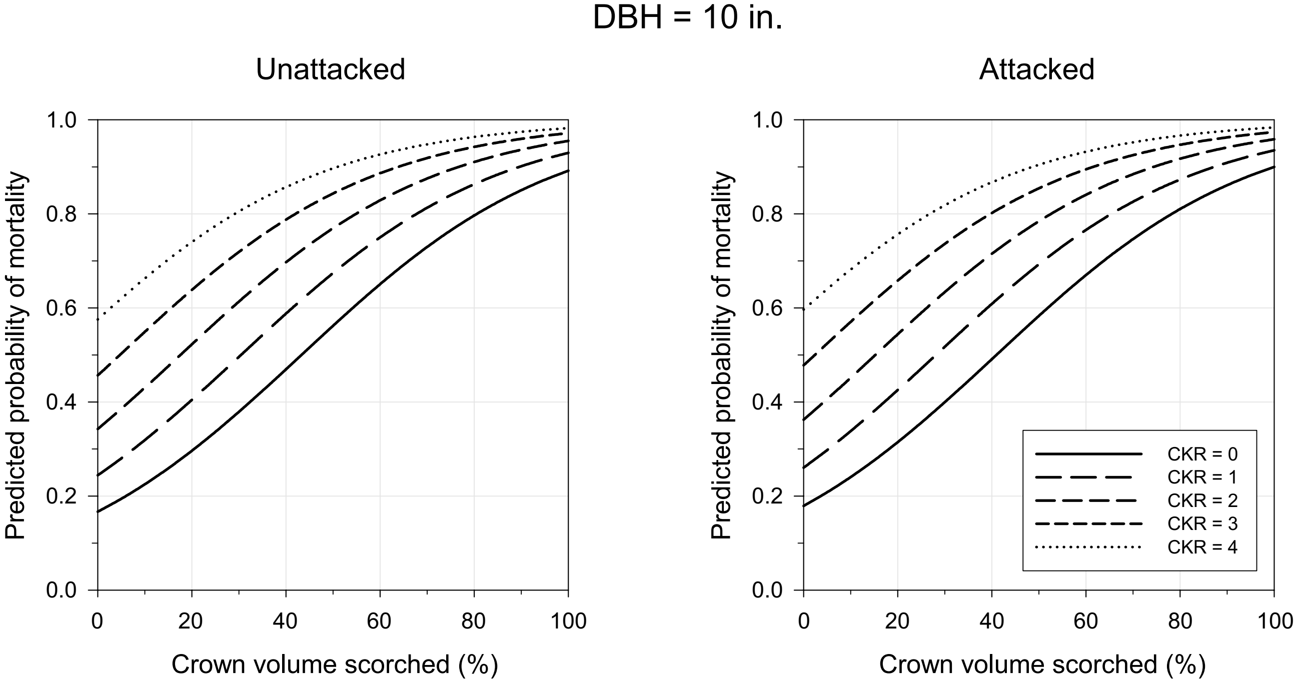


Figure A-2. Predicted probability of mortality curves by Cambium Kill Rating (CKR) and attack status for 10-inch DBH trees.

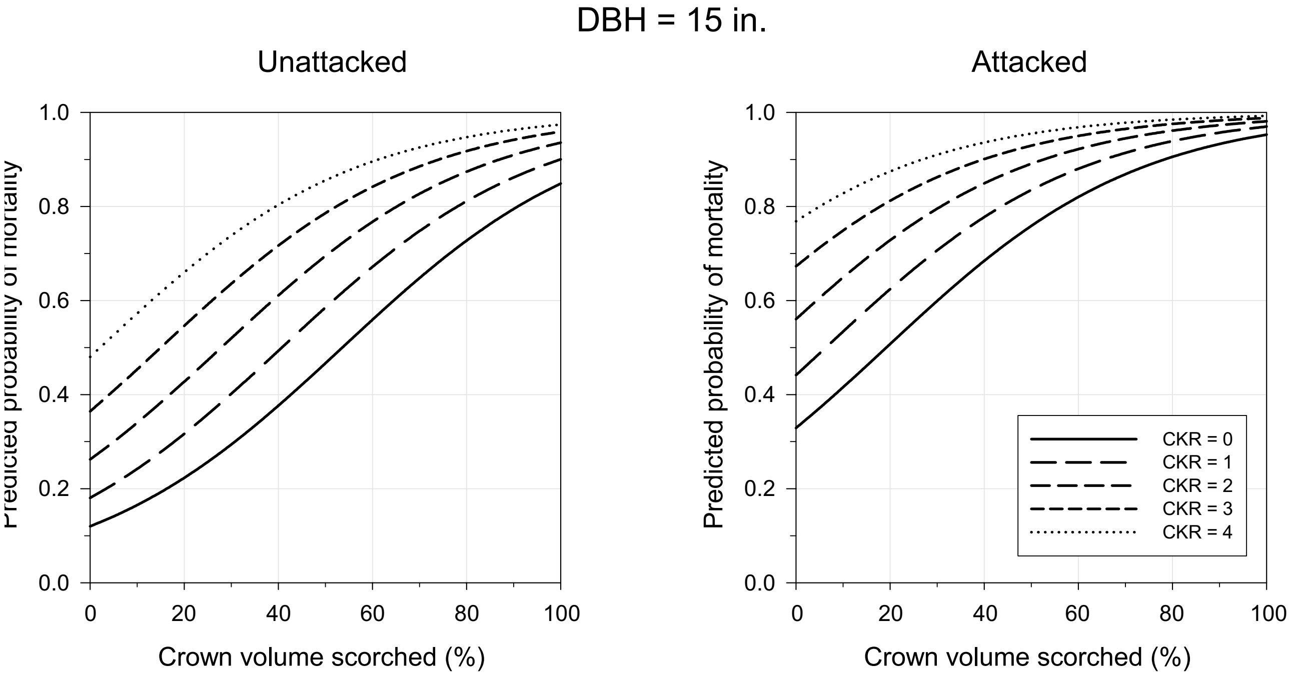


Figure A-3. Predicted probability of mortality curves by Cambium Kill Rating (CKR) and attack status for 15-inch DBH trees.

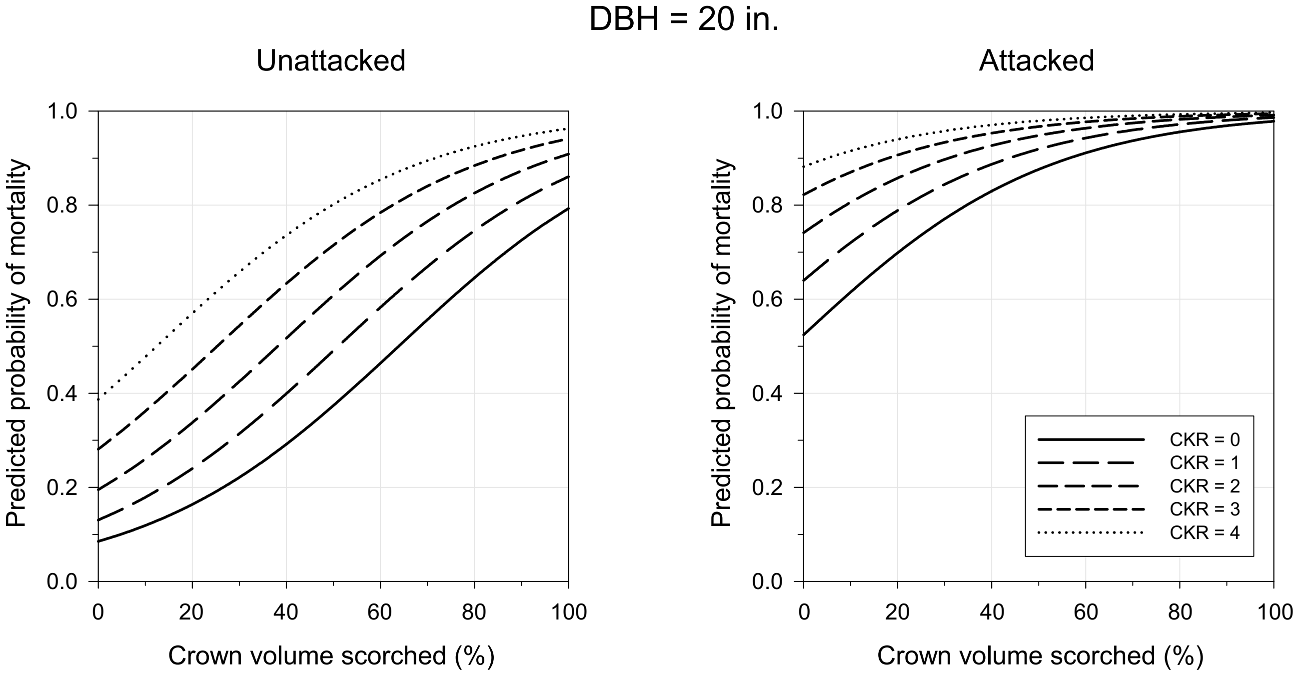


Figure A-4. Predicted probability of mortality curves by Cambium Kill Rating (CKR) and attack status for 20-inch DBH trees.

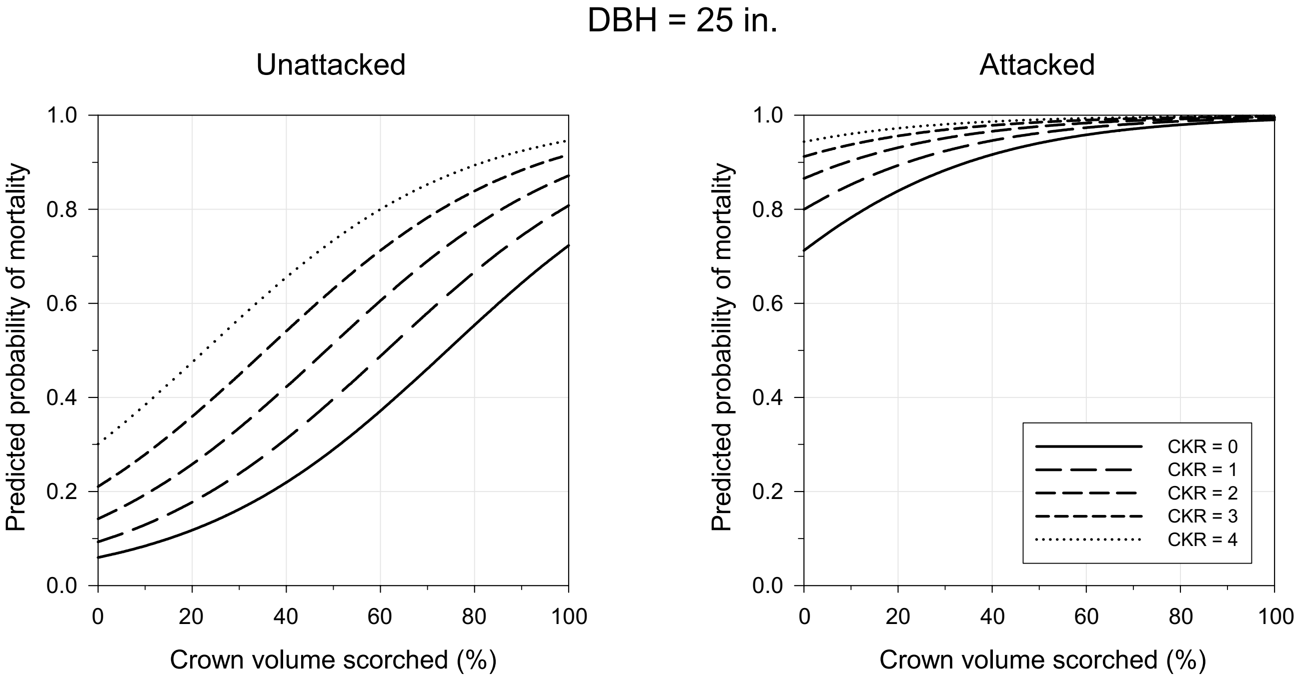


Figure A-5. Predicted probability of mortality curves by Cambium Kill Rating (CKR) and attack status for 25-inch DBH trees.

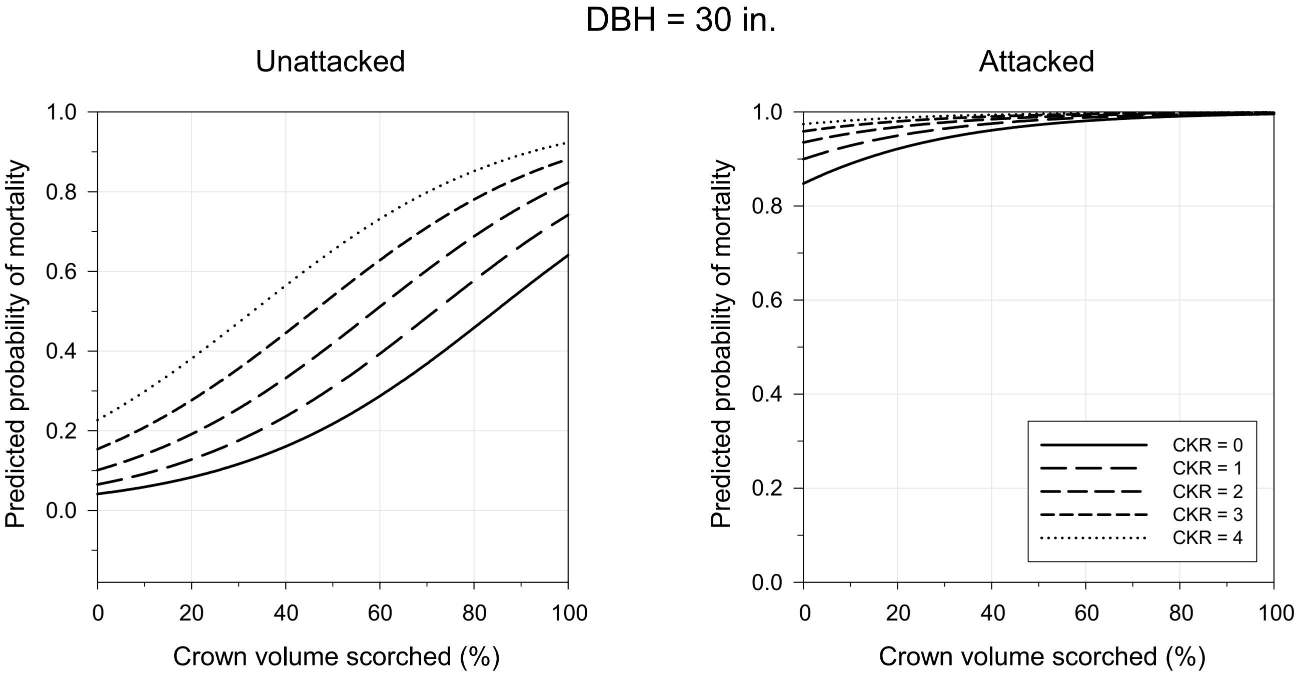


Figure A-6. Predicted probability of mortality curves by Cambium Kill Rating (CKR) and attack status for 30-inch DBH trees.

Appendix B: Attack Curves for a Range of Tree Sizes

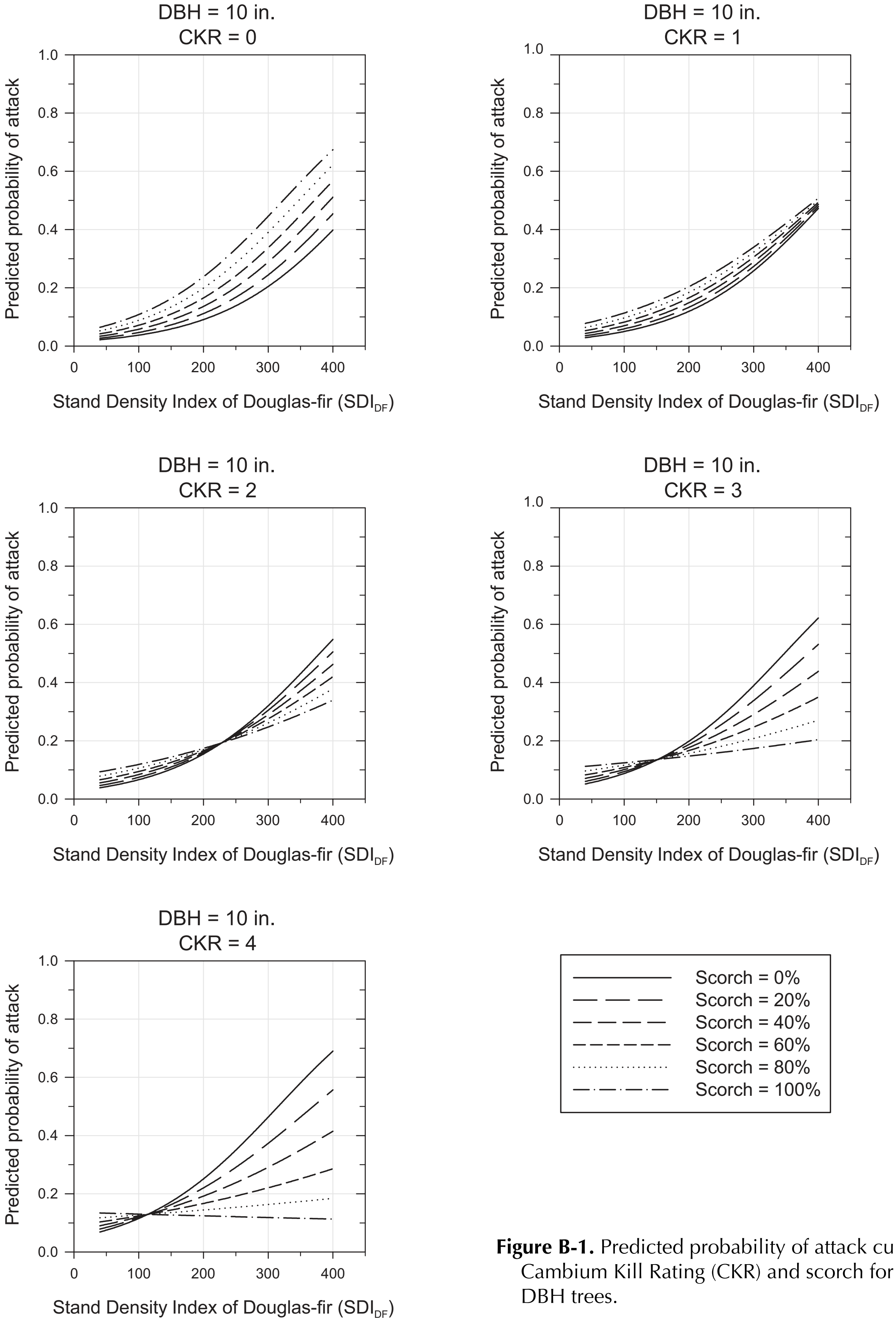


Figure B-1. Predicted probability of attack curves by Cambium Kill Rating (CKR) and scorch for 10-inch DBH trees.

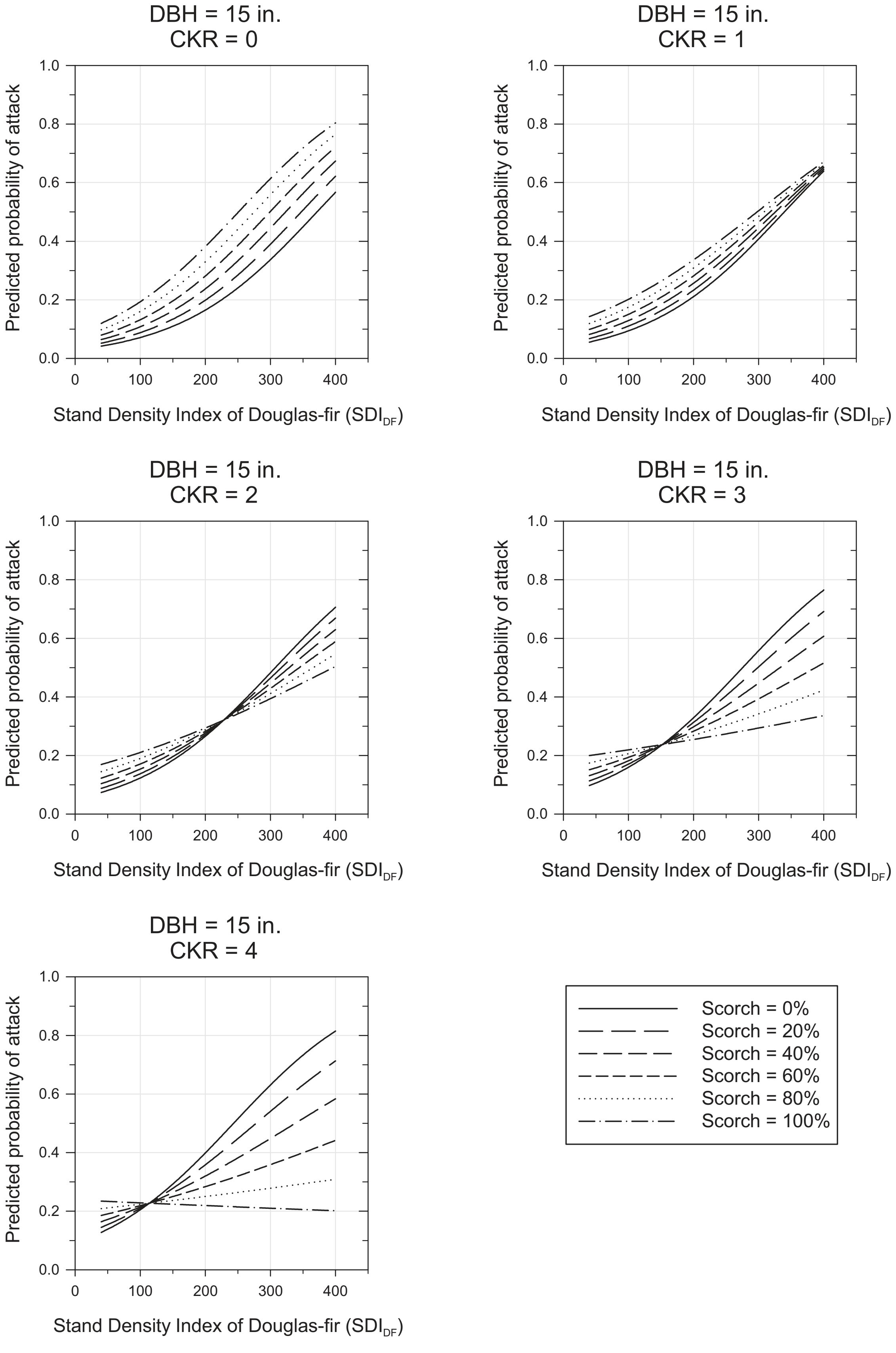


Figure B-2. Predicted probability of attack curves by Cambium Kill Rating (CKR) and scorch for 15-inch DBH trees.

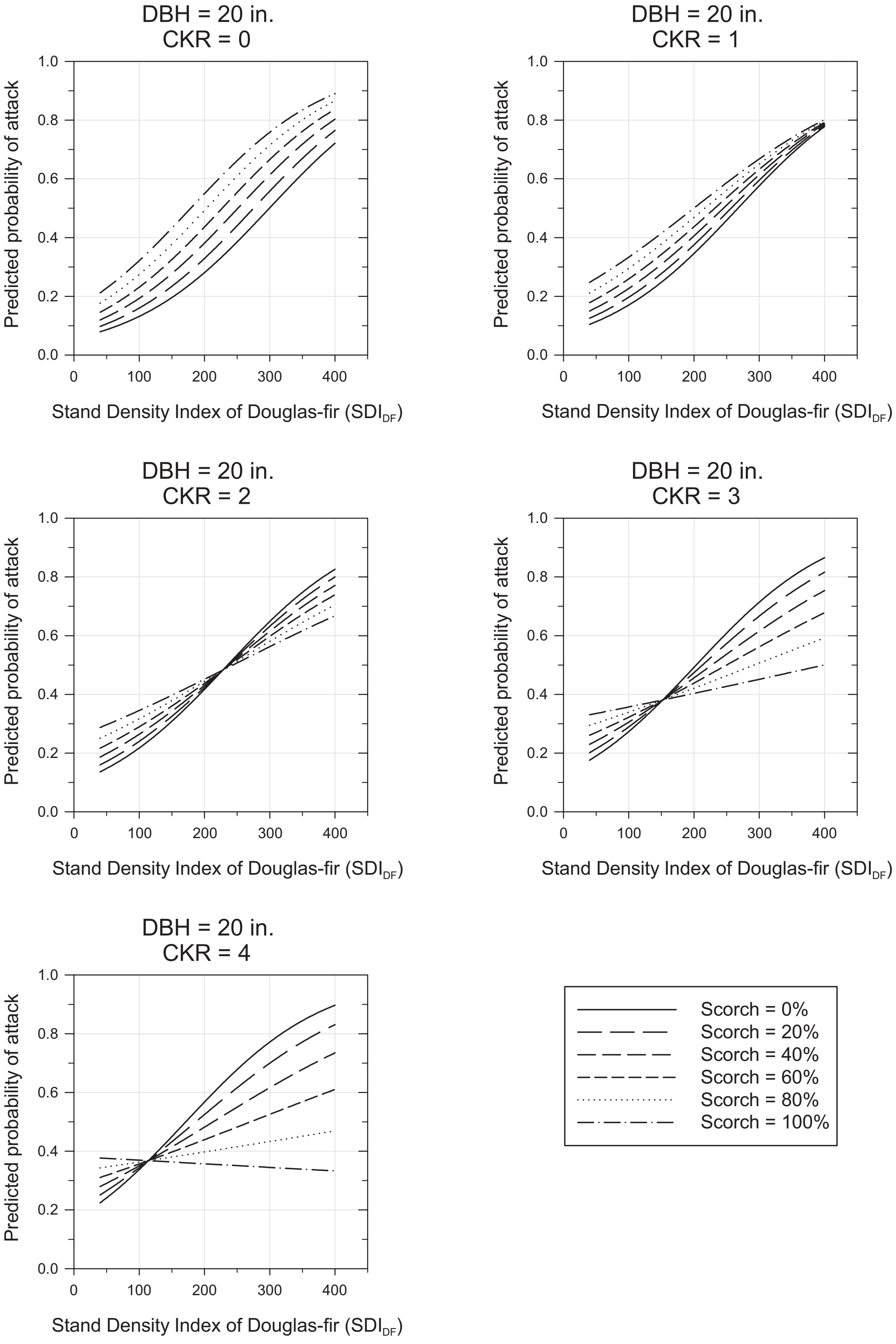


Figure B-3. Predicted probability of attack curves by Cambium Kill Rating (CKR) and scorch for 20-inch DBH trees.

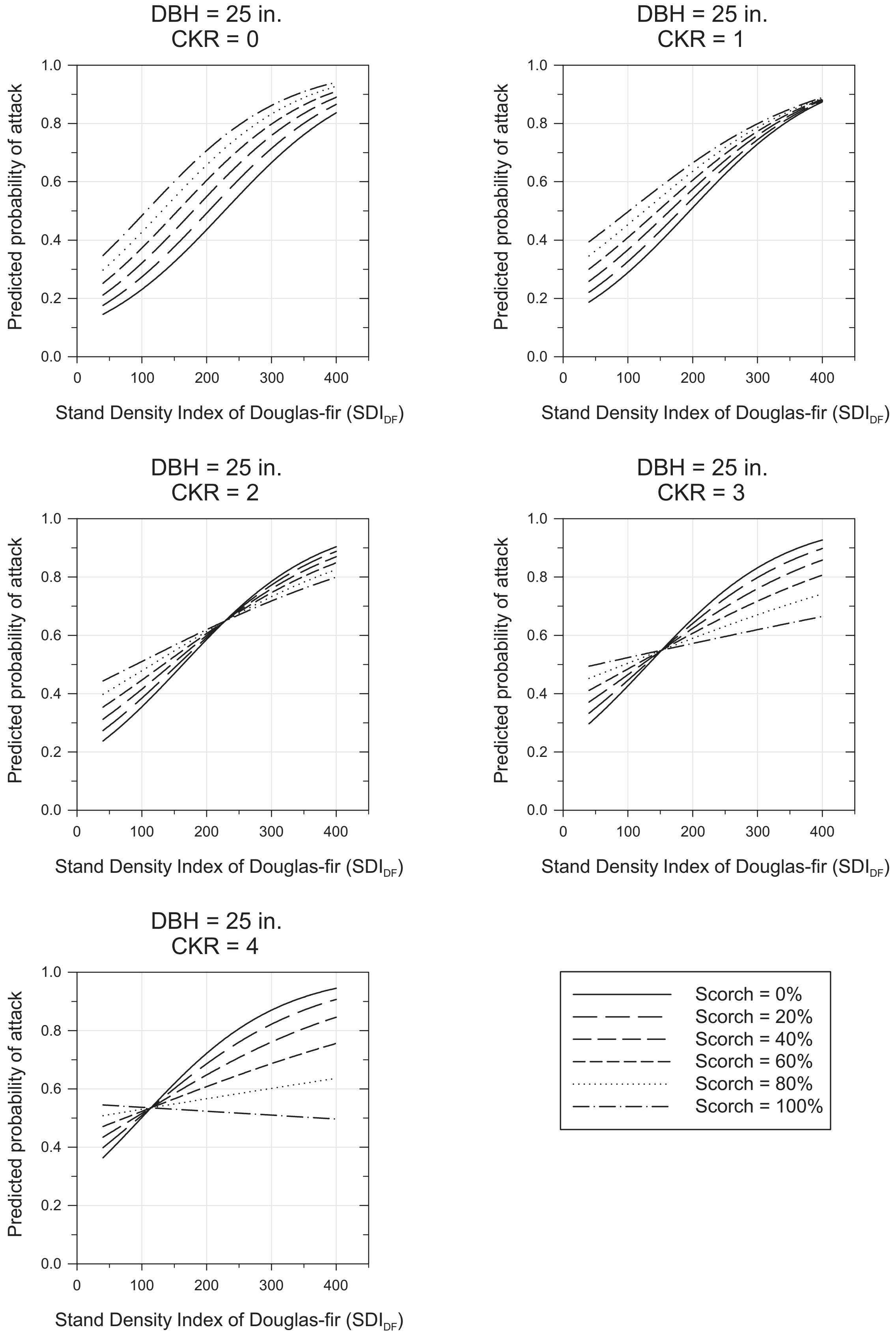
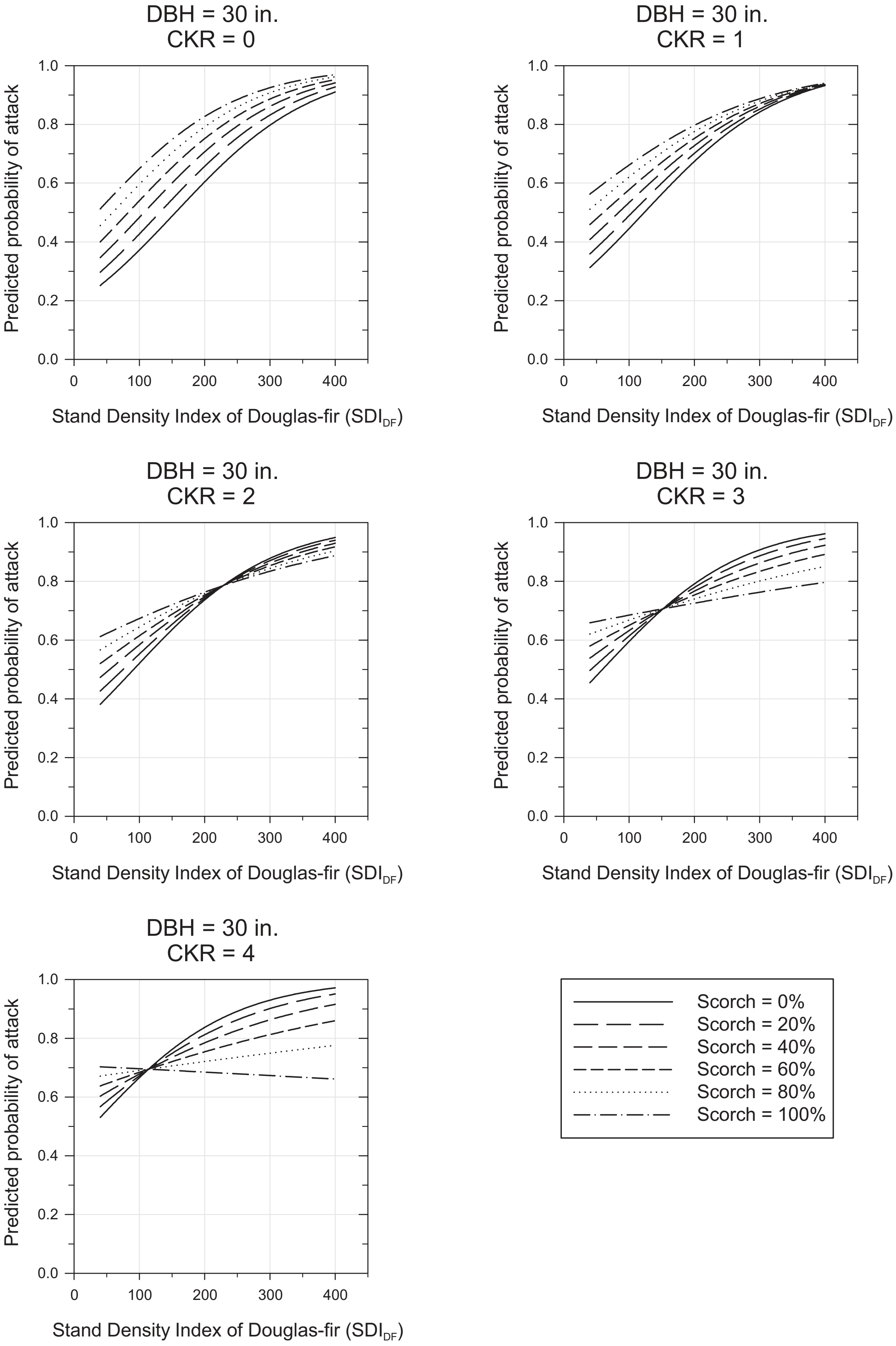


Figure B-4. Predicted probability of attack curves by Cambium Kill Rating (CKR) and scorch for 25-inch DBH trees.



DBH = 30 in.
CKR = 0

DBH = 30 in.
CKR = 1

DBH = 30 in.
CKR = 2

DBH = 30 in.
CKR = 3

DBH = 30 in.
CKR = 4

Figure B-5. Predicted probability of attack curves by Cambium Kill Rating (CKR) and scorch for 30-inch DBH trees.

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Assessing Post-fire Douglas-fir Mortality and Douglas-fir Beetle Attacks in the Northern Rocky Mountains

Supplement

United States Department of Agriculture / Forest Service
Rocky Mountain Research Station

General Technical Report RMRS-GTR-199 Supplement

September 2007

Hood, Sharon; Bentz, Barbara; Gibson, Ken; Ryan, Kevin; DeNitto, Gregg. 2007. **Assessing post-fire Douglas-fir mortality and Douglas-fir beetle attacks in the northern Rocky Mountains.** Gen. Tech. Rep. RMRS-GTR-199 Supplement. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 18 p.

Abstract

Douglas-fir have life history traits that greatly enhance resistance to injury from fire, thereby increasing post-fire survival rates. Tools for predicting the probability of tree mortality following fire are important components of both pre-fire planning and post-fire management. Hood and Bentz (2007) developed models for predicting the probability of Douglas-fir mortality and Douglas-fir bark beetle attack in the Northern Rocky Mountains based on fire injury and stand characteristics. This supplemental field guide to RMRS-GTR-199 provides reference photographs to help quantify injury level for use with the post-fire Douglas-fir mortality and bark beetle attack models. It also includes descriptions for measuring each characteristic in the field.

Upper left photo: Kevin Halverson estimates crown volume scorched.
Lower left photo: Jackie Redmer checks for cambium injury.

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Acknowledgments

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Introduction

This field guide is to be used in conjunction with the accompanying RMRS-GTR-199. Included are photographs depicting a range of fire-related injuries for Douglas-fir and associated descriptions and instructions for quantifying injury level in the field. The guide is intended for use with Douglas-fir greater than 5 inches in DBH. The characteristics included were found to be most significant in predicting post-fire Douglas-fir tree mortality and Douglas-fir bark beetle attack, and are used in models developed by Hood and Bentz (2007) and described in accompanying RMRS-GTR-199.

Percent Crown Volume Scorched

Percent crown volume scorched is assessed by visually estimating percent of pre-fire crown volume that was killed by fire. Scorched and blackened needles will soon drop from the crown. Therefore, crown scorch should be evaluated within 1 year post-fire. Figures 1 through 9 show a range of crown scorch. To evaluate crown scorch:

- First, position yourself in such a way that the entire tree crown is visible. Optimum viewing of the crown is at right angles to the direction of the fire spread and against a blue sky. It is important to stand back from the tree to fully view the entire crown.
- Next, reconstruct what the crown looked like before the fire. A tree with no bark and charred wood was dead before the fire. Pre-fire crown volume can be estimated by looking at the fine branch structure and needles. Branches lacking fine twigs were likely dead before the fire.
- Next, look at the overall appearance of the crown and estimate the percent of crown volume killed by fire based on your estimated pre-fire crown area. This includes any areas with brown, “frozen” needles, as well as any areas that have blackened fine branches. Blackened twigs may have some blackened needles remaining.

- Keep in mind overall crown shape. If, for example, the tree is cone shaped, 50 percent crown scorch may not equal 50 percent of the pre-fire crown length. Also, be sure to look at all sides of the tree. It is possible to have very high crown scorch on one side, but low crown scorch on the opposite side.

Cambium Kill Rating (CKR)

Cambium Kill Rating (CKR) is the number of dead cambium samples based on four samples per tree (fig. 10). The cambium, or phloem, is the living portion of the tree bole found between the bark and the wood (fig 11). To determine CKR:

- Nick bark away at ground-line using a hatchet on one side of the tree to expose the cambium (fig. 12). As small an area of bark as possible should be removed to prevent further injury to the tree. It is important to sample as close to the ground-line as possible, as this is where injury to the cambium from heat is most likely to occur. Douglas-fir has thick, light and dark colored bark, so be careful to bore completely through the bark to see this cambium layer.
- Once cambium is exposed, determine if it is live or dead.
  - Live tissue will feel moist, soft, and spongy, and will be a light pink, salmon color (fig. 13). Live cambium is pliable and usually, is easily peeled away from the wood and bark.
  - Dead cambium either will be hardened, with a dark, shiny appearance (fig. 14) or will feel sticky, with a darker color, and a sour smell (fig. 15). Sometimes the resin may have dried and have a whitish cast (fig. 16, lower area). Dead cambium will not easily separate from the wood and bark.
- Sometimes the sample will contain both live and dead cambium (fig. 16). In this situation, count the sample as live cambium.
- Continue sampling cambium in this way on four, evenly spaced areas of the tree and sum the dead cambium samples. CKR for the tree is the number of dead samples (for example, 0 to 4).

Table 1. Bark char codes and description of bark appearance (adapted from Ryan 1982).

Bark char code	Bark appearance
Unburned	Not burned
Light	Evidence of light scorching; can still identify species based on bark characteristics; bark is not completely blackened; edges of bark plates charred
Moderate	Bark is uniformly black except possibly some inner fissures; bark characteristics still discernable
Deep	Bark has been burned into, but not necessarily to the wood; outer characteristics are lost

To speed sampling time, bark char codes can be used instead of direct sampling of cambium (table 1, fig. 17), although doing so will reduce accuracy (fig. 1, GTR-199). When using bark char codes:

- Divide the tree bole into 4 quadrants (fig. 10).
- Assess each quadrant at ground-line to determine the bark char code. Bark char is often lighter higher on the bole than at ground-line, but only the area at ground-line should be considered. If the fire was low intensity and only the duff and litter burned, there may only be charring very low on the bole (fig. 18).
- Cambium beneath bark on a quadrant with unburned or light char can be assumed to be alive.
- Cambium beneath deep bark char can be assumed dead. Deep bark char is generally found only where an object near the tree base, such as a fallen tree, stump, or deep duff, burned for a long period of time.
- Direct sampling of cambium should be conducted if bark char is moderate because moderate bark char does not accurately predict if underlying cambium is live or dead.

Douglas-fir Beetle Attack-Level

Douglas-fir beetle adults are 0.16 to 0.24 inches long with a black body and reddish-brown wing covers (fig. 19). Douglas-fir beetles require live phloem for successful brood production and survival. Beetles also tend to attack trees growing in denser areas, with DBH greater than 9 inches. Attacked trees are identified based on external bole signs such as reddish-orange boring dust (fig. 18), a result of adult beetles chewing through bark into the inner cambium. Other insects may be found attacking fire-injured Douglas-fir. In particular, wood borers in the families Cerambycidae and Buprestidae produce a fine white granular boring dust rather than the reddish-orange dust produced by Douglas-fir beetle. Other insects only attack near the base of the tree, whereas Douglas-fir beetle attacks occur continuously along the height of the tree bole.

To assess Douglas-fir beetle attack status from ground-level:

- Look up the tree bole as high as possible for signs of boring. Initial attacks by Douglas-fir beetle typically occur high (~12 ft.) on tree boles with additional attacks above and below that height. The entire circumference of the bole should be examined, noting percent of bole circumference with signs of reddish-orange boring dust. Boring dust may be found between crevices on the bark and/or on the ground surrounding the bole of attacked trees.
- Clear resin flow or 'streamers' on the upper portion of a tree bole may be a sign of Douglas-fir beetle attack, but is often merely a tree response to fire injury. Therefore streamers are not a reliable indicator of beetle attack (fig. 20).
- To confirm presence of Douglas-fir beetle, a small portion of bark can be removed to reveal parent and larval galleries in the inner cambium (fig. 21).
- We estimate that trees with signs of boring dust on 10 percent to 90 percent of the bole circumference are strip-attacked and trees with greater than 90 percent of the bole circumference with boring signs are mass-attacked. Mass-attacked trees will die regardless of fire injury.

- When tallying data for the tree mortality model, all trees strip- and mass-attacked (greater than 10 percent of bole circumference with signs of boring) should be recorded as attacked. If boring dust is found on less than 10 percent of the tree bole, the tree is recorded as unattacked.

References

Hood, S. M.; Bentz, B. 2007. Predicting post-fire Douglas-fir beetle attacks and tree mortality in the Northern Rocky Mountains. Canadian Journal of Forest Research. 37: 1058-1069.

Ryan, K. C. 1982. Techniques for assessing fire damage to trees. In: Lotan, J., ed. Proceedings of the symposium: Fire, its field effects; 1982 October 19-21; Jackson, Wyoming. Missoula, MT: Intermountain Fire Council: 1-11.

Figure 1. Douglas-fir with 10 percent crown volume scorched. Only the lowermost branches and tips of some of the upper branches are scorched.

Figure 2. Douglas-fir with 20 percent crown volume scorched. The scorch on this tree is higher on one side than the other, as shown by the diagonal line delineating the uppermost scorch. This pattern of crown scorch is often seen in steep areas.

Figure 3. Douglas-fir with 30 percent crown volume scorched. Even though this tree had branches fairly low on the bole, the lower branches were spaced far apart and are shorter, accounting for less pre-fire crown volume than the mid- to upper-portions of the tree crown.

Figure 4. Douglas-fir with 40 percent crown volume scorched. Crown scorch is most accurately assessed by standing far enough back to view the whole crown. If the area is on a steep slope, move uphill or to the side of the tree in question, as done in this picture, to frame the crown against a blue sky.

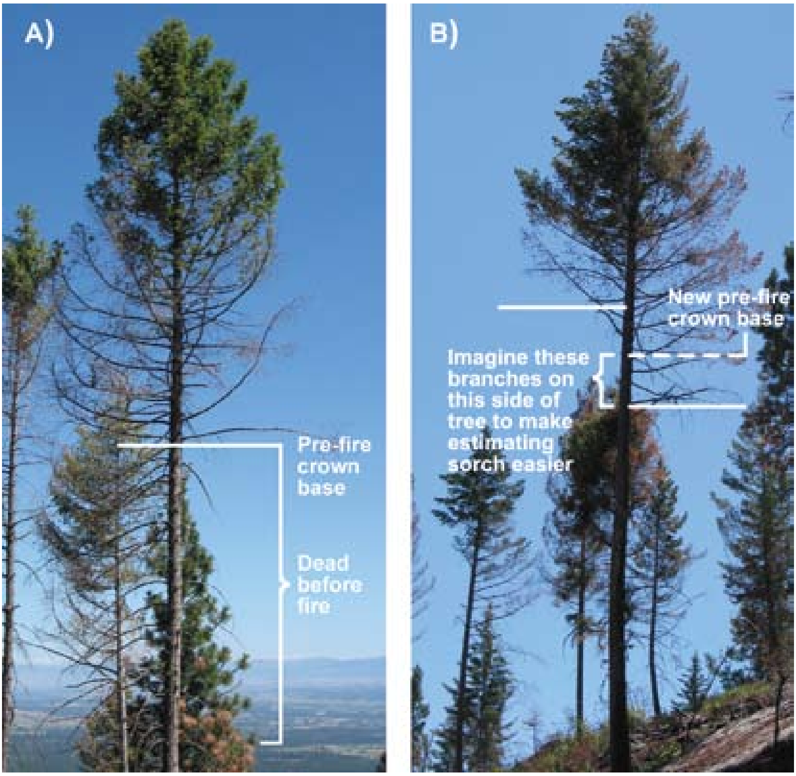

Figure 5. Douglas-fir with 50 percent crown volume scorched. A) The short, lower branches of this tree were dead before the fire and should not be included when determining crown scorch. Branches that were dead before the fire will not have any fine twigs and will often be broken off. B) Trees often have unsymmetrical crown bases as seen here. It may help to "move" some of the lower branches to the other side of the crown to even out the crown bases and then estimate crown scorch based on this new crown shape.

Figure 6. Douglas-fir with 60 percent crown volume scorched. A) Be careful to look at all sides of the tree–the crown scorch is much lower on the back side of this tree. B) A tree with high scorch on all sides of the crown. The lower, short branches were dead before the fire. Be careful to include only the branches that have fine twigs when estimating pre-fire crown volume.

Figure 8. Douglas-fir with 90 percent crown volume scorched. Very few green needles remain in the crown with this high level of crown scorch.

Figure 7. Douglas-fir with 80 percent crown volume scorched.

Figure 9. Douglas-fir with 100 percent crown volume scorched. Green needles are absent in the crown.

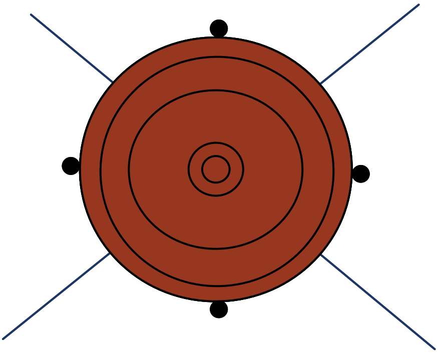

Figure 10. Cross-section of tree showing placement of cambium samples to determine cambium kill rating (CKR). Black circles represent placement of direct cambium samples. Cambium should be sampled as close to the ground-line as possible. The lines show how to divide the tree bole into four bark char quadrants when using bark char codes in place of direct cambium sampling.

Figure 11. Cross-section of Douglas-fir showing cambium layer between bark and wood. In this photo, the cambium is seen as a dark band because it is dead.

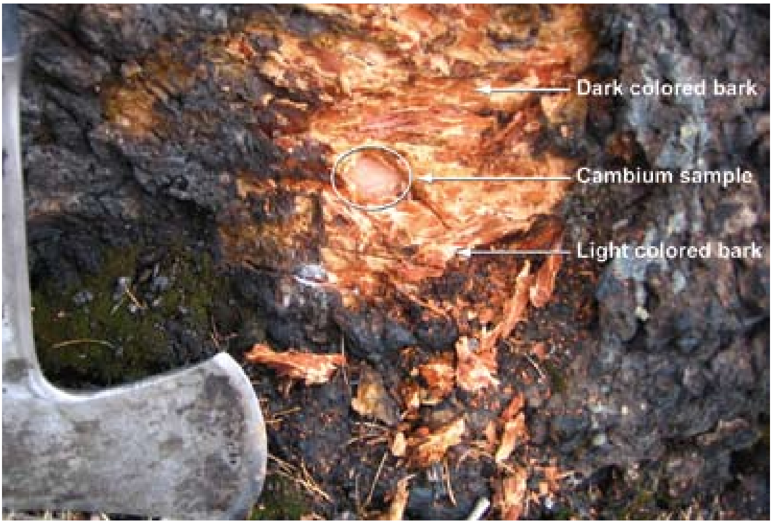

Figure 12. Use a hatchet to expose a small section of cambium at groundline to determine cambium status. The cambium seen here is live. Douglas-fir bark has both light and dark sections. Be careful to chop completely through the bark to expose the cambium.

Figure 13. Live Douglas-fir cambium is salmon colored, moist, spongy, and pliable.

Figure 14. Dead Douglas-fir cambium. The cambium here has dried up to a very thin layer that cannot be separated from the wood beneath it.

Figure 15. Dead Douglas-fir cambium is darker in color. It may have a sour smell and be moist; however, it will feel sticky and is not spongy.

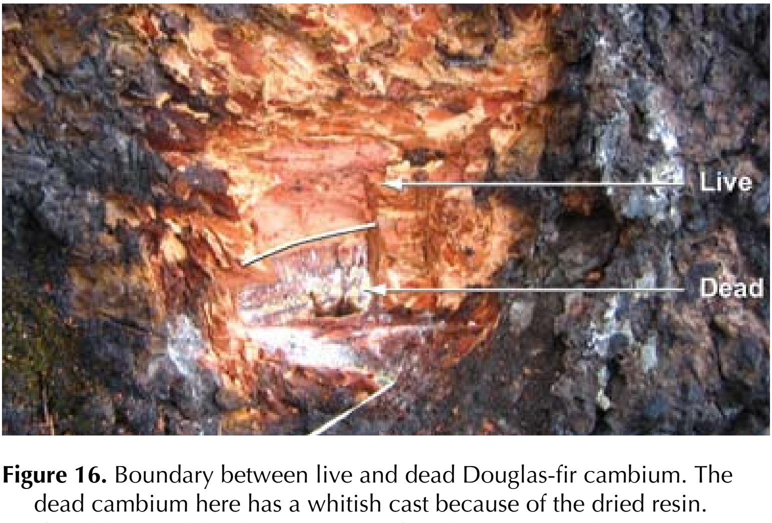

Figure 16. Boundary between live and dead Douglas-fir cambium. The dead cambium here has a whitish cast because of the dried resin. If both live and dead cambium are found in one sample, count the sample as live for purposes of determining cambium kill rating (CKR).

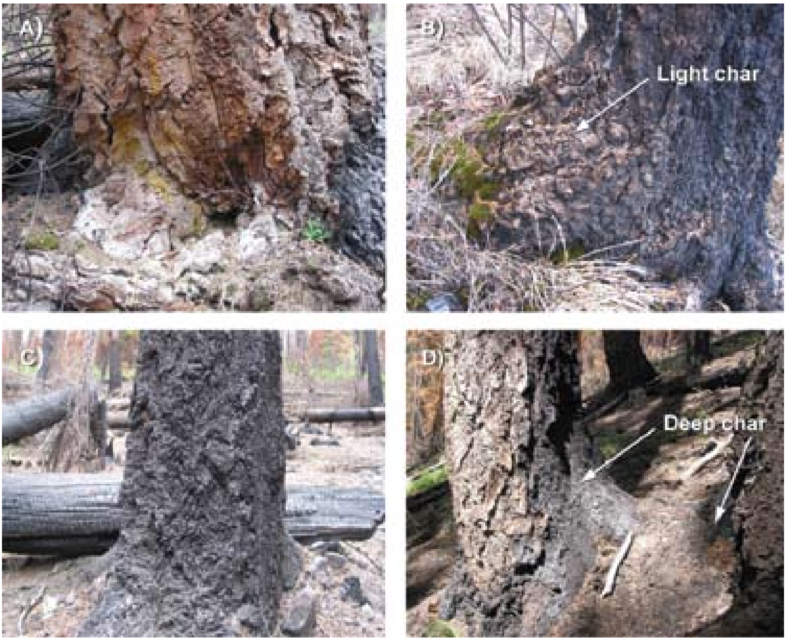

Figure 17. Bark char on Douglas-fir. A) unburned bark, B) light bark char, C) moderate bark char, D) deep bark char. See table 1 for a description of each bark char code.

Figure 18. Sharp transition between unburned and moderate bark char. The bark char is very low on the tree due to low intensity fire burning only the duff and litter around the tree. When using bark char codes, always examine the area of bark nearest the ground-line to determine the correct code. The orange piles of boring dust on the bole are from Douglas-fir beetle attacks.

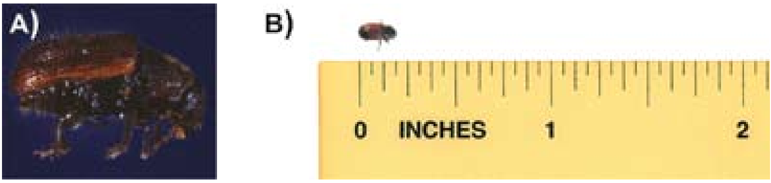

Figure 19. A) Enlarged picture of Douglas-fir beetle to show detail. B) Life-sized Douglas-fir beetle.

Figure 20. Streamers of pitch are not a reliable indicator that the tree is attacked by Douglas-fir beetle.

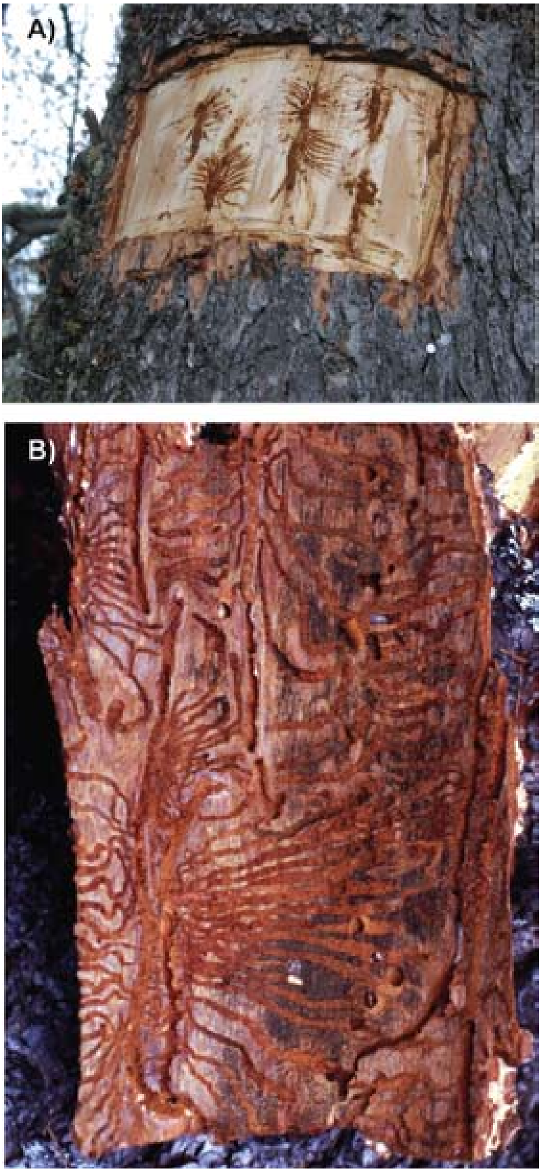

Figure 21. Douglas-fir beetle galleries. Each bark beetle species constructs a unique gallery pattern. A) The Douglas-fir beetle galleries here are within weeks of attack and are not fully developed. B) Fully developed Douglas-fir beetle galleries.

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