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A Field Guide to Predict Delayed Mortality of Fire-Damaged Ponderosa Pine: Application and Validation of the Malheur Model

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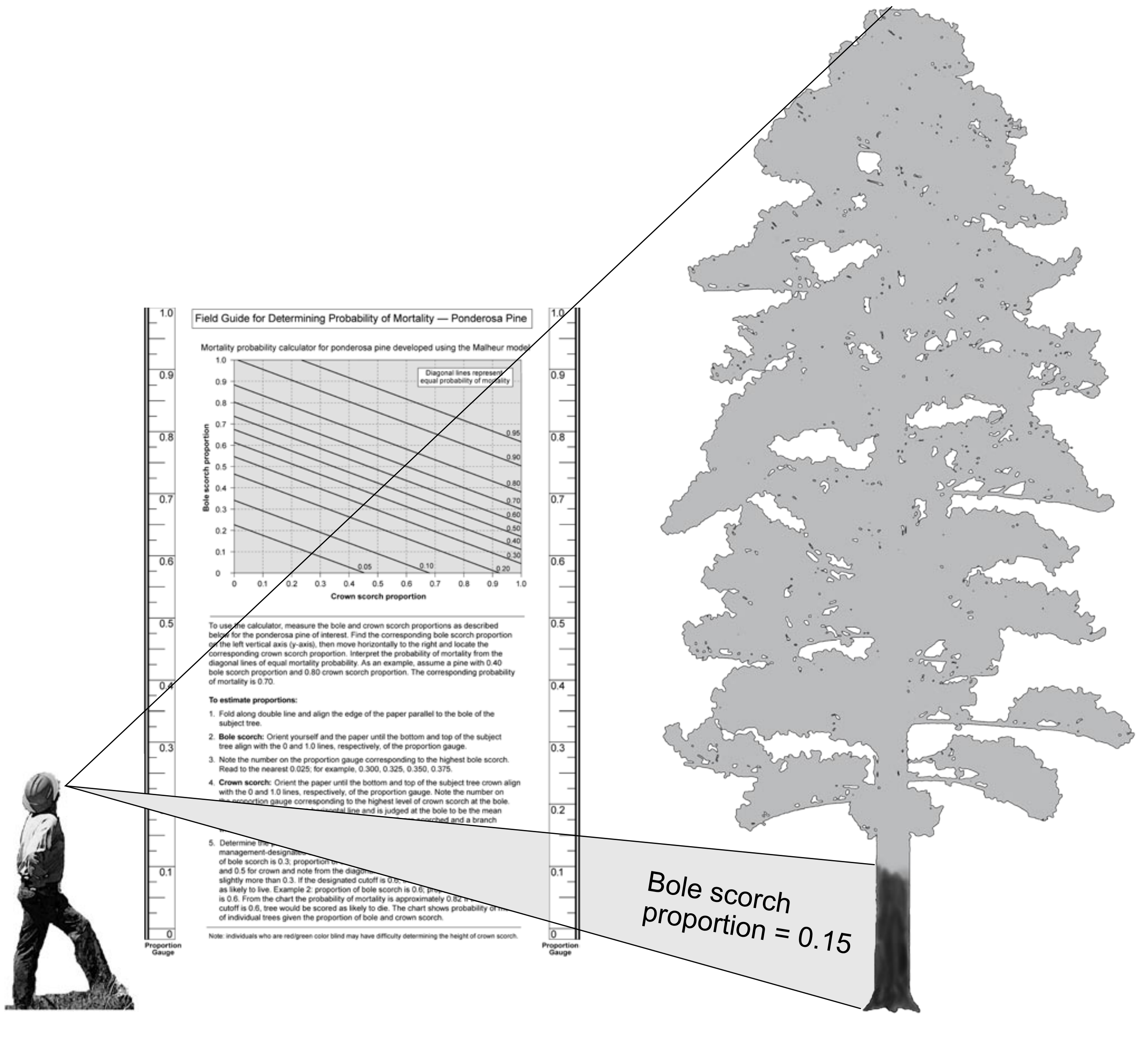

Authors

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Abstract

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The Malheur model for fire-caused delayed mortality is presented as an easily interpreted graph (mortality-probability calculator) as part of a one-page field guide that allows the user to determine postfire probability of mortality for ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.). Following both prescribed burns and wildfires, managers need the ability to predict the mortality of individual ponderosa pine trees based on burn damage. The model was developed from fire-caused delayed mortality observed for 4 years postburn in a replicated study of 12 burn units and 6 nonburned units near Burns, Oregon. During the fourth year, the percentage of mortality on burned units was not statistically different from that on nonburned units. Here we report validation data from 3,237 ponderosa pines in 10 additional burns, observed for 3 years postburn, from the southern Blue Mountains and northern California that indicate a good fit between mortality predicted by the Malheur model and observed mortality. Tear-out copies of the field guide on water proof paper are provided.

Keywords: Blue Mountains, fire, ponderosa pine, big trees, delayed mortality.

Introduction

The Malheur model is a two-variable model developed from data collected following prescribed burns on the Malheur National Forest near Burns, Oregon (Thies et al. 2005, 2006). Fire-caused delayed mortality of ponderosa pines (*Pinus ponderosa* Dougl. ex Laws.) was surveyed annually for 4 years postburn. During the 4th year, the percentage of mortality on burned units was not statistically different from that on nonburned units. In the subsequent 6 years postburn (for a total of 10 years), the percentage of mortality on burned units remained at a low level similar to that on nonburned units. The model was used to generate a graph called the "mortality-probability-calculator" or "the calculator." The calculator allows a user to quickly determine the probability of mortality of fire-damaged ponderosa pine. Because the model predicts the probability of mortality for individual trees based on surface damage that reflects underlying physiological damage, it is valid for trees damaged by either prescribed fire or wildfire.

Prescribed burning and wildland fire are being used as tools to achieve specific management objectives in western interior forests of the United States. Following a burn, managers need the ability to predict the mortality of individual trees. Mortality is evaluated to determine the success of burning prescriptions to achieve such management objectives as postfire stocking levels and to improve future prescriptions, and for all fires to better plan postfire activities such as hazard tree removal and restoration of wildlife habitat and watershed quality. Postfire mortality predictions need to be based on easily observable morphological and burn-damage characteristics that can be quickly assessed in the field. The Malheur model meets these criteria for ponderosa pine. Details of the model development and the study it was based on are published elsewhere (Thies et al. 2005, 2006).

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We present the Malheur model here in graph form as a two-factor mortality-probability calculator, and describe its use in a one-page field guide (app. 1) along with a list of cautions. Tear-out copies of the field guide are provided at the back of this GTR. In addition, a test of the efficacy of this model using data from 10 validation stands from the south end of the Blue Mountains in eastern Oregon and the east side of the Cascade Range in northern California is provided (app. 2). The 10 validation stands were not the same as those used for model development (fig. 1).

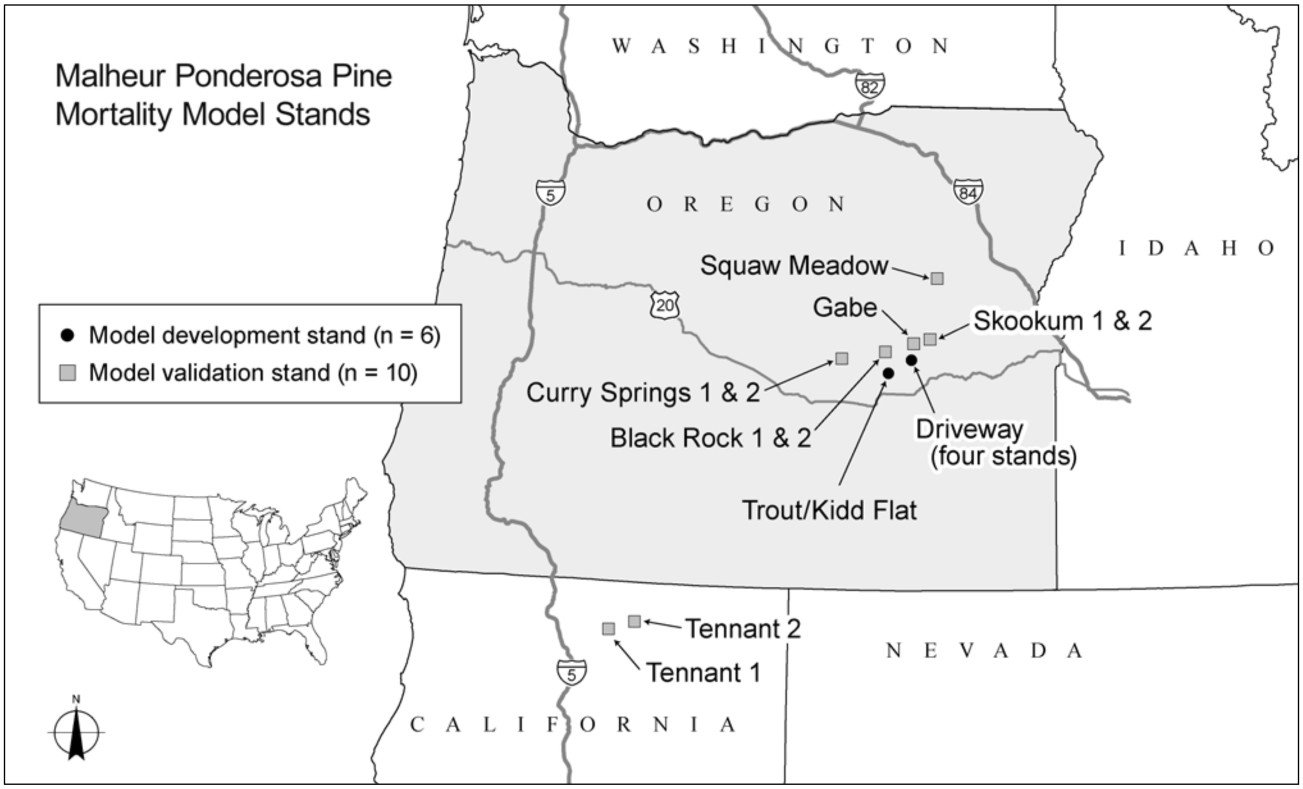

Figure 1—Location of stands used to collect Malheur model development and validation data.

Using the Mortality-Probability Calculator

A tree is evaluated by first measuring the proportion of both bole and crown scorch. **Bole scorch proportion** is the maximum bole scorch (blackened) height as a proportion of total tree height (fig. 2). **Crown scorch proportion** is the length of the scorched (scorched or consumed needles) portion of the crown as a proportion of the total crown (fig. 2). The crown base is taken as the lower height of live crown (whorl of three or more live branches) as it existed prefire. The layer of scorched crown is often asymmetrical. The height of the scorched crown is taken as the average height for that layer measured at the bole. The proportion can be calculated by using heights measured with an instrument, such as a laser rangefinder with inclinometer or hand-held clinometer, or determined directly by something as simple as the proportion gauge provided on the one-page field guide. The mortality-probability calculator is used by locating a tree's bole scorch proportion on the left vertical axis (the y-axis) and then moving horizontally to the right until reaching the crown scorch proportion. The value of the intercept point is the probability of mortality for that tree, determined from the nearest upper and lower diagonal lines of equal probability of mortality. The probability of mortality could be interpolated to the nearest 0.01 although that degree of precision may exceed most operational requirements.

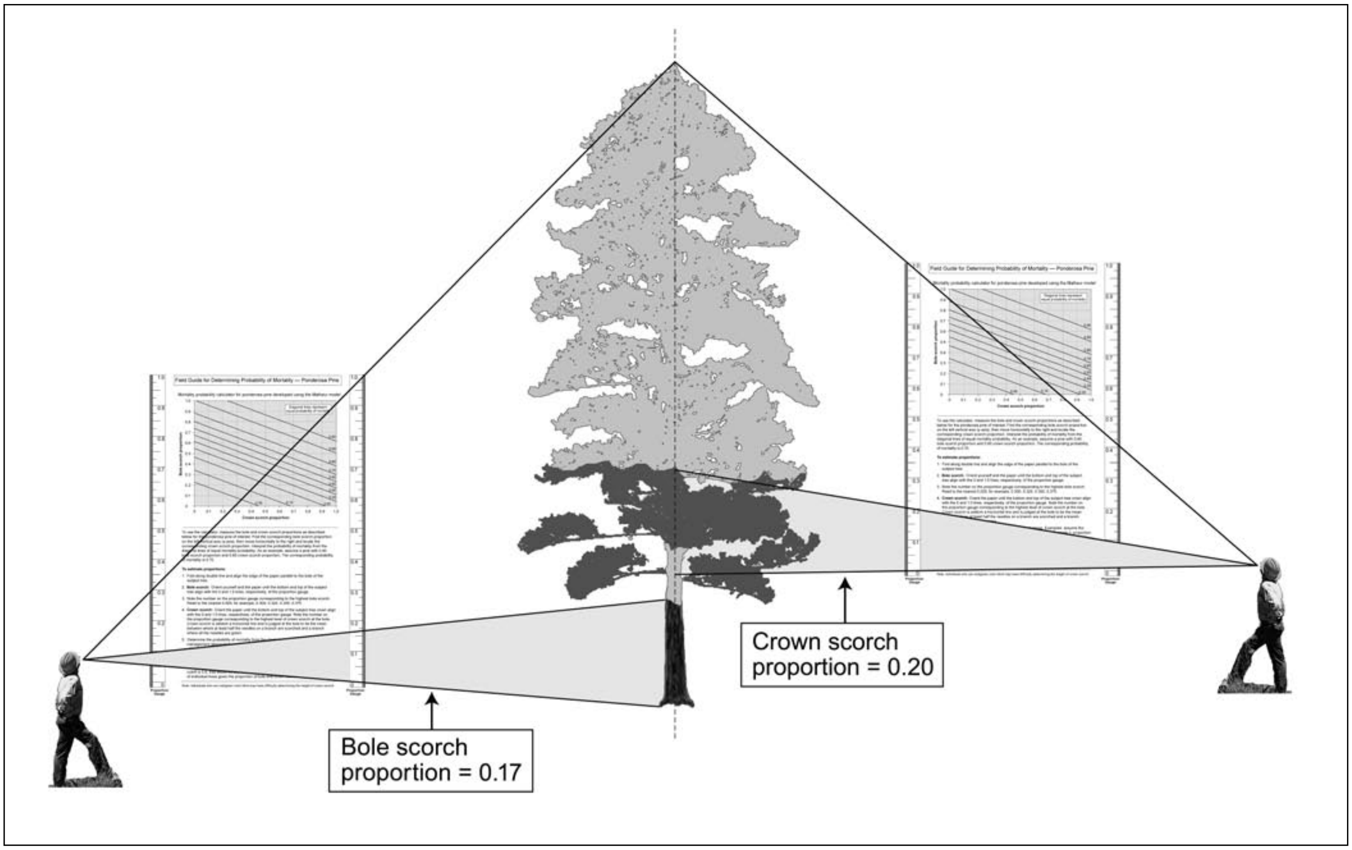

Figure 2—Measuring the proportions of bole scorch and crown scorch.

This two-variable mortality-probability calculator was derived for each 0.1 increment of probability of mortality from 0.0 to 1.0 (plus probabilities of 0.05 and 0.95) by holding the probability constant while proportion of crown scorch was increased by increments of 0.1 and using the model to solve for the corresponding proportion of bole scorch. The points were plotted resulting in straight lines representing points of equal probability of mortality.

Management Decision Tool

Use of the information from the Malheur model is determined by the objectives and needs of the land manager. Individual trees can be evaluated for probability of mortality, or a stand can be surveyed (sampled) and the proportion of trees projected to die can be determined. Probability of mortality for trees can be determined in the field using the calculator, or stem and crown scorch proportions can be recorded in the field and probability of mortality can be calculated in a spreadsheet.

This tool can be used to monitor (1) whether objectives were met for prescribed burns and wildland fire use, or (2) to determine if economical salvage opportunities exist after wildfire in consideration of other management objectives.

Individual tree example—

A management objective may require that all trees with a probability of mortality greater than 0.6 be marked for removal. Example 1: Proportion of bole scorch is determined to be 0.3; proportion of crown scorch is determined to be 0.5. Enter the calculator at 0.3 for bole scorch and 0.5 for crown scorch and find the intercept point. Note from the diagonal lines that the probability of mortality is slightly more than 0.3. If the designated probability limit is 0.6, the example tree would not be marked.

Example 2: Proportion of bole scorch is 0.6; proportion of crown scorch is 0.6. Enter the calculator at 0.6 for bole scorch and 0.6 for crown scorch and find the intercept point. Note from the diagonal lines that the probability of mortality is approximately 0.82. If the management designated mortality probability limit is 0.6, the tree would be marked for removal. The probability limit is established from management considerations.

If access to the subject trees makes frequent returns possible, the limit may be established high (e.g., 0.9) with a plan to return to remove additional trees that die. If the area is remote, thereby making frequent returns difficult, the limit may be established low (e.g., 0.3) with an intent to cut most of the trees that will likely die from the fire with a single entry.

Survey example—

A management objective may require that an estimate be made of the proportion of trees in a stand that will die. Perhaps the manager needs to learn at an early date the success of a particular prescription or to evaluate the need to replant. It is important that sample trees be randomly selected and representative of the stand or the portion of the stand of interest. Each sample tree would be evaluated and its probability of mortality recorded. A mean of the probabilities will be an estimate of the proportion of the trees in the stand that can be expected to die. For example, assume that 10 trees are representative and randomly selected from an area of interest and they have the following probabilities of mortality: 0.40, 0, 0, 0.55, 0, 0, 1.0, 0, 0.65, and 0.55. The total is 3.15; the proportion of trees likely to die in the stand is 3.15/10 or 0.315. Although the sample size in this example is unrealistically small, it illustrates the math involved.

Cautions

Every model must be used with caution to ensure that the sample population being tested is within the limits of the data used to develop the model. The following considerations are provided for the Malheur model:

1. Evaluate only ponderosa pine. Although results for other species may appear to conform to the results for ponderosa pine, it is unlikely that such is the case. Additional testing would be required to adjust the model for other species.
2. Sample within the geographic area of model development or where validation data from representative stands have been tested and results from the model have been shown to be a good fit to the observed data. (Note: At this writing the successfully tested geographic area of inference for the Malheur model ranges from the southern Blue Mountains of eastern Oregon south into northern California (app. 1, fig. 2).
3. Obtain the most accurate measurement possible to determine the bole and crown scorch proportions consistent with management objectives. Avoid ocular estimates as they will likely differ by observer and thus not yield consistent results.
4. The model provides a probability of mortality for a given tree and not an absolute indication that a tree will live or die. A probability of 0.6 means that if 1,000 trees have crown and bole scorch proportions that fall on the 0.6 line of probability, about 600 of them can be expected to die. All trees with a bole and crown scorch proportion that places them above the 0.6 probability line have a greater than 0.6 probability of mortality.
5. Because the model provides a probability, some trees predicted to live will die and some that are predicted to die will live. This was observed in stands used for both model development and validation. With or without fire, a few trees are likely to die in a stand each year because of other natural processes such as insects, disease, or limited resources. Additionally, a few trees with crown or bole scorch proportion equal to 1.0 will survive. Because of these anomalies, the model predicts a probability of mortality within the range from 0.011 to 0.972, rather than 0.0 to 1.0. The Malheur model will predict fire-caused mortality close to what would be observed in the next 3 years if the stand were undisturbed; however, the stands are biological systems and some small variation from the predicted mortality should be expected.

The model provides a probability of mortality and not an absolute indication that a tree will live or die.

6. The model predicts probability of mortality based on damage to individual trees and is not related to fire type or season of the burn. Data used to develop the model were collected from areas of prescribed burns; however, the sample trees encompassed the full range of burn-induced-damage from mild heat exposure and no visible damage to extreme burn damage with no chance of recovery. To access the full range of responses in these stands, data were collected from both spring and fall burns. The tested explanatory variables represented tree morphology, fire damage, and season of burn. After accounting for the fire damage variables, there was no indication of a difference in mortality between fall and spring burns. This was interpreted to mean that trees with similar degrees of damage from either burn season would have about the same probability of delayed mortality. We concluded that the mortality is related to the damage inflicted on each tree rather than the season as it relates to the physiological state of the trees. Because mortality is related to the damage inflicted, the type of fire is not important, and this model, although developed with data from prescribed burns, will work equally well with trees burned by a wildfire. One of the fires in the validation data set reported in appendix 1 was a prescribed burn that escaped and burned the stand as a wildfire. The data from that fire fit the Malheur model well and supports use of the model on trees damaged by wildfire.

Acknowledgments

Creation of the Malheur model has taken a sustained effort from 1996 through 2008 by many individuals through a variety of funding channels. The authors thank the Malheur National Forest, the Emigrant Creek Ranger District, and the Burns Interagency Fire Zone for their support throughout this effort. Without their constant and unselfish support this project would not have been possible. Fieldwork was conducted with funds provided by Forest Health Protection of the U.S. Department of Agriculture, Forest Service, through the Special Technology Development Program, the Pacific Northwest Research Station, and the Joint Fire Sciences Program. Special thanks to Mike Dubrasich of Forest Analytics of Lebanon, Oregon, for statistical review of the manuscript and to Karen Esterholdt for editing the manuscript. We also thank Paul Anderson, Erik Berg, Kenneth Higle, and Rick Kelsey for review and helpful comments during manuscript preparation.

English Equivalents

When you know	Multiply by	To find
Centimeters (cm)	0.394	Inches
Meters (m)	3.28	Feet

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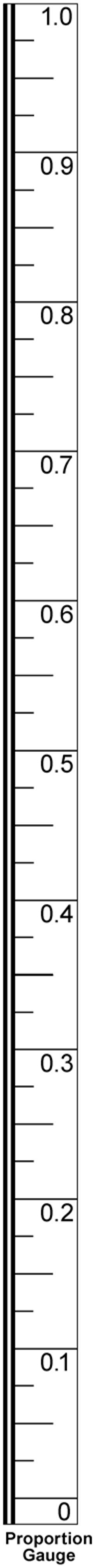
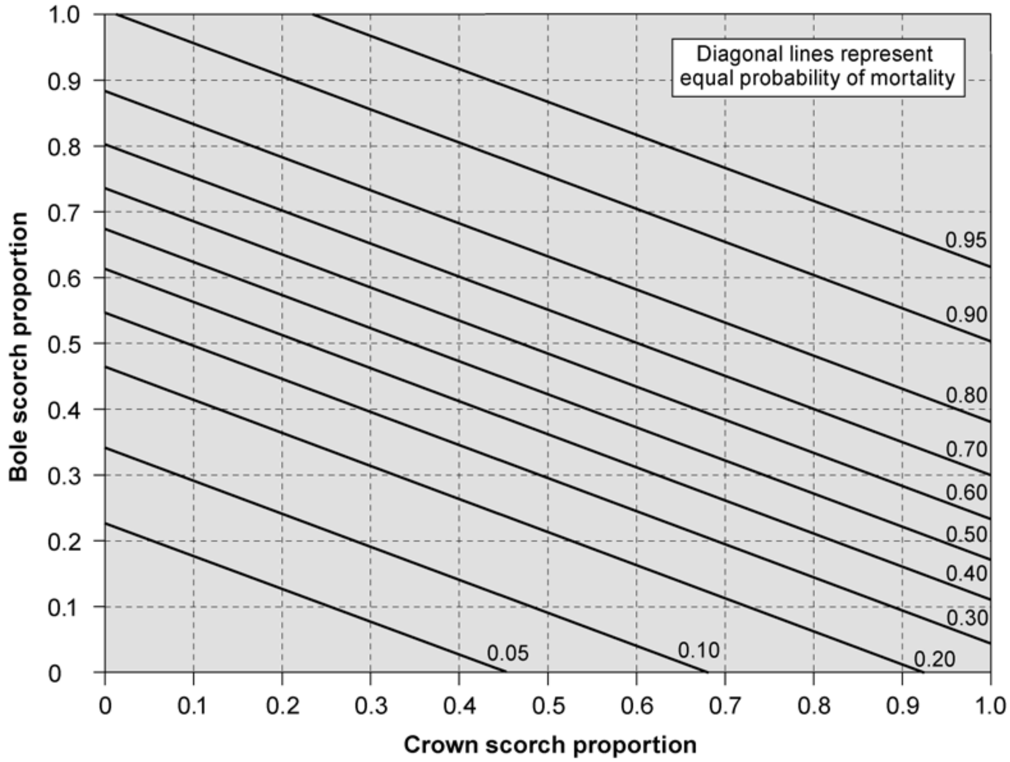
Appendix 1—Field Guide



Field Guide for Determining Probability of Mortality — Ponderosa Pine

Mortality probability calculator for ponderosa pine developed using the Malheur model

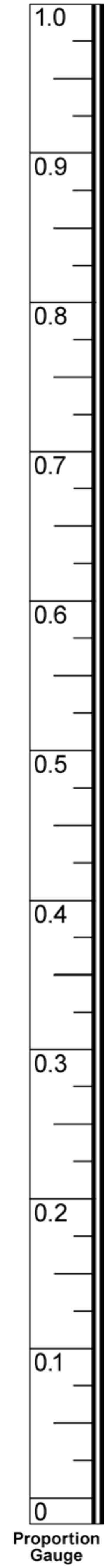


To use the calculator, measure the bole and crown scorch proportions as described below for the ponderosa pine of interest. Find the corresponding bole scorch proportion on the left vertical axis (y-axis), then move horizontally to the right and locate the corresponding crown scorch proportion. Interpret the probability of mortality from the diagonal lines of equal mortality probability. As an example, assume a pine with 0.40 bole scorch proportion and 0.80 crown scorch proportion. The corresponding probability of mortality is 0.70.

To estimate proportions:

1. Fold along double line and align the edge of the paper parallel to the bole of the subject tree.
2. **Bole scorch:** Orient yourself and the paper until the bottom and top of the subject tree align with the 0 and 1.0 lines, respectively, of the proportion gauge.
3. Note the number on the proportion gauge corresponding to the highest bole scorch. Read to the nearest 0.025; for example, 0.300, 0.325, 0.350, 0.375.
4. **Crown scorch:** Orient the paper until the bottom and top of the subject tree crown align with the 0 and 1.0 lines, respectively, of the proportion gauge. Note the number on the proportion gauge corresponding to the highest level of crown scorch at the bole. Crown scorch is seldom a horizontal line and is judged at the bole to be the mean between where at least half the needles on a branch are scorched and a branch where all the needles are green.
5. Determine the probability of mortality from the chart above. Examples: assume the management-designated cutoff for probability of mortality is 0.6. Example 1: proportion of bole scorch is 0.3; proportion of crown scorch is 0.5. Enter the chart at 0.3 for bole and 0.5 for crown and note from the diagonal lines that the probability of mortality is slightly more than 0.3. If the designated cutoff is 0.6, the example tree would be scored as likely to live. Example 2: proportion of bole scorch is 0.6; proportion of crown scorch is 0.6. From the chart the probability of mortality is approximately 0.82 if the designated cutoff is 0.6, tree would be scored as likely to die. The chart shows probability of mortality of individual trees given the proportion of bole and crown scorch.

Note: individuals who are red/green color blind may have difficulty determining the height of crown scorch.



Appendix 2: Malheur Model Validation

Introduction

The Malheur two-factor model, presented here in graph form as the mortality-probability calculator, predicted 96.4 percent of the observed mortality caused by the prescribed burns used for model development (Thies et al. 2006). But a model remains a hypothesis until it is validated by using data unrelated to the developmental data. We report here the results of an effort to validate the Malheur model in a limited area by evaluating sample trees in burns in 10 ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) stands in the southern Blue Mountains of eastern Oregon and the east side of the Cascade Range in northern California. The 10 validation burns are in different stands than the 12 burns used to collect data for model development.

Methods

Validation stands (fig. 1, table 1) were identified and data collection begun within a month following their respective burns from fall 2002 through fall 2004. Stands were selected according to accessibility of a prescribed burn, available cooperation from Forest Service ranger districts, and geographic distribution of sites. The number of trees tagged in each stand was dependent on staff time and funding.

Within each stand, a starting point was selected near an access road in a portion of the stand typical of that burn. A random starting azimuth was selected within the azimuth range that would encompass the range of fire damage observed. If the first transect was not long enough to provide adequate numbers of trees, the crew

Table 1—Stand summary for validation stands

Stand name	Latitude/longitude	Area	Elevation	Burn date	Mean d.b.h.[a]	Mean height
		Hectares	*Meters*		*Centimeters (range)*	*Meters*
Black Rock 1	43.88N, 118.86W	60	1595	Fall 2004	27.8 (8.9–85.1)	13.9
Black Rock 2	43.95N, 118.82W	90	1650	Fall 2004	24.1 (7.6–96.5)	12.2
Curry Springs 1	43.93N, 119.63W	30	1685	Fall 2002	37.8 (12.2–101.9)	19.3
Curry Springs 2	43.91N, 119.61W	30	1670	Spring 2003	41.2 (8.6–95.0)	20.7
Gabe	44.11N, 118.75W	55	1585	Fall 2004	43.2 (10.4–95.0)	21.3
Skookum 1	44.10N, 118.41W	30	1645	Fall 2002	42.7 (15.7–78.7)	21.3
Skookum 2	44.12N, 118.42W	30	1650	Spring 2003	43.6 (8.9–104.6)	21.2
Squaw Meadow	44.50N, 118.43W	90	1760	Fall 2004	24.6 (7.6–76.5)	13.8
Tennant 1	41.58N, 121.93W	240	1240	Fall 2004	39.1 (7.9–192.0)	18.3
Tennant 2	41.65N, 121.67W	45	1480	Fall 2004	34.9 (8.6–208.3)	16.8

[a] d.b.h. = diameter at breast height.

offset 50 to 100 m within the burn and continued along the back azimuth. The strip sampled extended 5 m to either side of the transect centerline. All standing ponderosa pine greater than 7.5 cm diameter breast high (d.b.h.) within the sampling strip were tagged. A numbered aluminum tag was placed on each tree, in numerical order, at breast height toward the transect centerline.

Each tagged tree was evaluated and marked at the time of transect establishment as either alive (if the tree had some green needles) or dead (if all needles were scorched or discolored owing to heat from the fire). Dead trees were categorized by time of death as preburn mortality (based on bark condition, presence of decay, and lack of needles and fine twigs), immediate mortality (alive at the time of the burn but dead when tagged), and delayed mortality (found dead in later exams, table 2).

Table 2—Summary of tree means sampled from the 10 validation stands

Stand name	Trees alive at burn	Trees dead after 3 years	Mortality
			Percent
Black Rock 1	298	42	14.1
Black Rock 2	294	35	11.9
Curry Springs 1	121	12	10.0
Curry Springs 2	249	24	9.6
Gabe	300	17	5.7
Skookum 1	289	35	12.1
Skookum 2	296	14	4.7
Squaw Meadow	300	80	26.7
Tennant 1	731	91	12.5
Tennant 2[a]	359	71	19.8

[a] The Tennant 2 burn began as a prescribed burn; however, the fires got out of control and created a wildfire situation. Sampling on this unit was done in the area of the wildfire using the same protocol as for other validation units.

At the time of tagging, morphological variables were recorded for each tagged tree. The d.b.h. of each tagged tree was measured to the nearest 0.25 cm on the uphill side of the tree at 1.37 m above mineral soil, and the height was measured to the nearest 3.0 cm with a laser rangefinder with inclinometer (table 1). Two measures of fire-caused damage were recorded for each tree: crown scorch proportion and bole scorch proportion.

Crown scorch proportion is the proportion of damaged crown length based on scorched or consumed needles. The total crown length is the distance from the tree tip to the lower height (whorl of three or more live branches) of live crown as it existed prefire. Immediately postfire, crowns that are alive but damaged show two layers: an upper green layer and a lower brown layer of scorched or consumed needles. Damage layers often were asymmetrical. The scorch height was taken as the average height for that layer measured at the bole. Heights were measured to the nearest 3.0 cm with a laser rangefinder with inclinometer. Crown scorch proportion as a measure of crown damage has been used by others and allowed reproducible results with a minimum of training of field crews (Thies et al. 2006).

Bole scorch proportion is the maximum bole scorch height as a proportion of total tree height. Bole scorch is the distance from mineral soil to the highest point of bole blackening measured to the nearest 15 cm.

Only those tagged trees living at the time of the prescribed burns were included in this validation evaluation. Each fall, starting with the first growing season after the burn, sample transects were revisited and delayed mortality recorded; trees without any green needles, and not previously marked as dead, were recorded as having died that growing season.

We tested the agreement between the mortality predicted by the Malheur model and the mortality observed 3 years postburn of tagged trees from the 10 validation stands using the Hosmer-Lemeshow goodness of fit test, the receiver operating characteristic (ROC) scores, and percentage of correctly classified trees. The Hosmer-Lemeshow goodness of fit test was used to evaluate the fit of the full and reduced (Malheur) models to the development data (Thies et al. 2006) and the Malheur model to the validation data. The data were first partitioned into groups based on the predicted probability of mortality (table 3). We classified the mortality probabilities from 0.0 to 1.0 into 10 groups identified by the midpoints (0.5 to 0.95). The sum of the predicted probability of mortality of all trees in a decile was used as the projected number of trees expected to die in that class. The actual observed status of the trees 3 years postburn (alive, dead) was recorded for each decile from the observed dead trees. If the Malheur model is accurate, then the projected

Table 3—Calculated mortality and observed mortality for the Malheur model across the range of probability of mortality classes

	Probability-of-mortality classes, by midpoint percentage										
Data set	**5**	**15**	**25**	**35**	**45**	**55**	**65**	**75**	**85**	**95**	**Total**
						Number					
Validation data set:											
Total trees in class—	2,380	304	151	94	65	58	52	44	37	52	3,237
Projected dead	75	44	37	33	29	32	33	33	32	50	398
Observed dead	72	31	24	34	33	36	39	37	34	46	386
Development data set:[a]											
Total trees in class—[a]	2,315	280	162	130	153	99	82	78	59	57	3,415
Projected dead[a]	64	41	40	46	69	54	53	59	50	54	530
Observed dead[a]	80	44	29	43	60	67	56	61	55	55	550

[a] From Thies et al. 2006.

number of dead trees should be close to the observed number of dead trees. The Hosmer-Lemeshow test statistic (HL) was calculated by comparing the observed and expected frequencies of the dead trees in the decile groups. The test statistic has a chi-square distribution with a desirable outcome of nonsignificance ($P > 0.05$), thereby indicating that the model prediction does not significantly differ from the observed data (Hosmer and Lemeshow 2000, van Mantgem et al. 2003). The ROC analysis paralleled that done by Saveland and Neuenschwander (1990) to evaluate models of tree mortality following fire damage. The ROC curve is a plot of the sensitivity (y-axis) and 1-specificity (x-axis) over all possible mortality probability cutoff values. Sensitivity is the ability to correctly predict a tree to die (proportion of tree deaths that were predicted). Specificity is the ability to correctly predict a tree to live (proportion of surviving trees that were predicted). The area under the curve is a measure of the ability of the model to discriminate between dead and alive trees. The ROC area values range from 0 to 1.0. A value for the area under the curve of 1.0 indicates a perfect model, which would yield no false positives. The ROC values ≥0.7 are acceptable; values ≥0.9 are indicative of outstanding discrimination (Hosmer and Lemeshow 2000).

Results and Discussion

Within the 10 validation stands, 3,237 ponderosa pine were evaluated. The Malheur model had a good fit to the data from the validation stands (table 3): HL = 10.31, d.f. = 8, P = 0.244. The Malheur model predicted a total mortality of 398 trees based on the two measured variables of fire damage. Three growing seasons postburn the actual observed mortality was 386 trees, a difference of 3.1 percent of the predicted mortality from the observed mortality. Table 3 illustrates the fit of the model across the range of probability-of-mortality classes. These results closely parallel the Malheur model fit to the data from the 3,415 ponderosa pine in the model development data set (Thies et al. 2006).

The ROC curve is presented as figure 3; the area under the curve is 0.8815 (standard error 0.01134; 95-percent confidence interval of 0.8593 to 0.9038; $P < 0.0001$) indicating a good fit between the predicted and the observed outcomes.

We used classification tables as a supplemental measure of model fit. For our analyses, 0.5 was selected a priori as the decision criterion. That is, trees with predicted probability of mortality, ≥0.5 are predicted dead. We used this cutoff criterion because we had no reason for selecting otherwise. A cutoff of 0.5 was used previously for fire-killed ponderosa pine (Regelbrugge and Conard 1993), for fire-killed Douglas-fir (Ryan et al. 1988), and is considered the most common cutoff used in a variety of applications (Hosmer and Lemeshow 2000). A classification

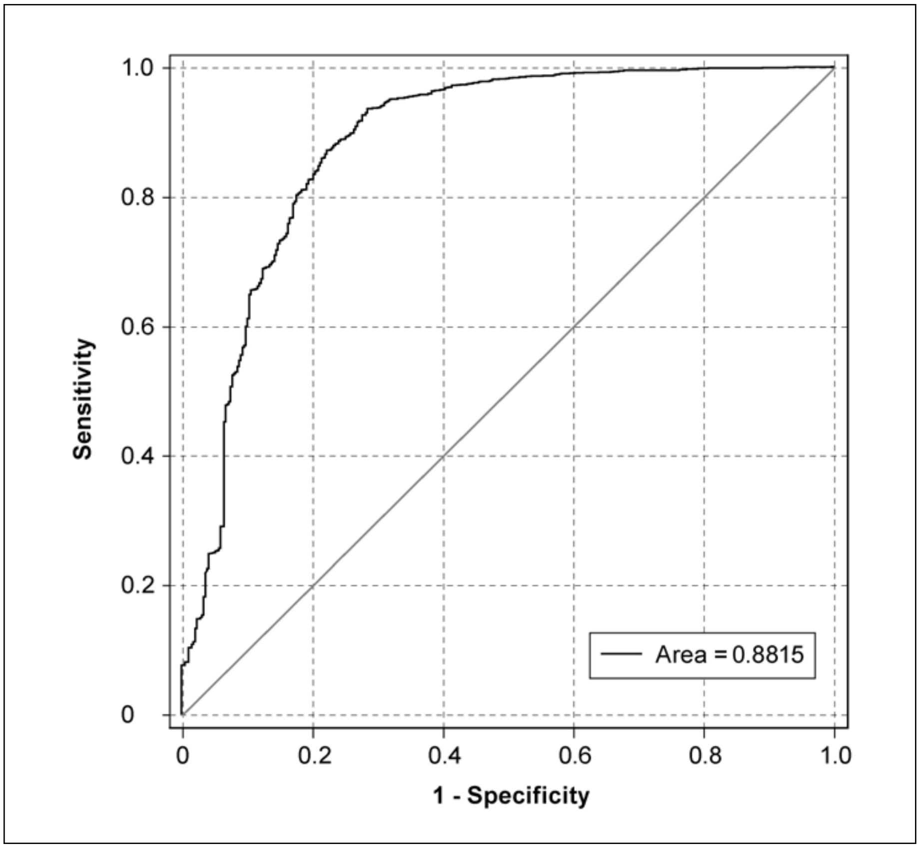


Figure 3—The ROC curve representing the relationship between the Malheur model and the validation data with the area under the curve being equal to 0.8815 (n = 3,237). Sensitivity is the false positive and specificity is the false negative.

table was prepared for the validation data set (table 4). The overall rate of correct classification was 92.4 percent. The overall rates of correctly predicting mortality of individual trees was 79.0 percent.

The Malheur model fits the available data for wildfire-like conditions. One of the stands included in the validation set (Tennant 2) was a prescribed fire that

Table 4—Classification table of the validation data set based on the Malheur model logistic regression using a cutoff of 0.5 probability of mortality

	Observed		
Predicted	**Alive**	**Dead**	**Total**
Alive *P*(m) <0.5	2,800	194	2,994
Dead *P*(m) >0.5	51	192	243
Total	2,851	386	3,237

Overall rate of correct classification = [(2,800 + 192)/3,237] × 100 = 92.4 percent.
Overall rate of correctly predicting mortality = 192/243 × 100 = 79.0 percent.

escaped and burned much of the unit as a wildfire. The sample transects were placed in the wildfire portion of the stand, and the data were collected from sample trees (n = 359) using the same protocols followed for the other nine stands from which validation data were collected. The area under the ROC curve for Tennant 2 is 0.8925 (standard error 0.02379; 95-percent confidence interval of 0.8459 to 0.9391; P < 0.0001) indicating a good fit between the predicted and the observed outcomes. A classification table was prepared for the Tennant 2 data (table 5). The

Table 5—Classification table of the Tennant 2 data set based on the Malheur model logistic regression using a cutoff of 0.5 probability of mortality

	Observed		
Predicted	**Alive**	**Dead**	**Total**
Alive *P*(m) <0.5	272	25	297
Dead *P*(m) >0.5	16	46	62
Total	288	71	359

Overall rate of correct classification = [(272 + 46)/359] × 100 = 88.6 percent.
Overall rate of correctly predicting mortality = 46/72 × 100 = 74.2 percent.

overall rate of correct classification was 88.6 percent. The overall rate of correctly predicting mortality was 74.2 percent. Similar results were observed for the nearby (fig. 2) Tennant 1 successfully conducted prescribed burn. The Tennant 1 unit (n = 731) has an area under the ROC curve of 0.9378 (standard error 0.0125; 95-percent confidence interval of 0.9132 to 0.9623; P < 0.0001. A classification table was prepared for the Tennant 1 data (table 6). The overall rate of correct classification was 93.6 percent, and the overall rate of correctly predicting mortality was 83.3 percent (table 6). We consider this evidence that individual trees respond to their fire-induced damage and trees with similar damage characteristics will have a similar probability of mortality whether the damage is induced by a prescribed fire or a wildfire.

The Malheur model can be used to determine probability of fire-caused delayed mortality in individual trees regardless of whether the fire is a prescribed fire or a wildfire.

Table 6—Classification table of the Tennant 1 data set based on the Malheur model logistic regression using a cutoff of 0.5 probability of mortality

	Observed		
Predicted	**Alive**	**Dead**	**Total**
Alive *P*(m) <0.5	629	36	665
Dead *P*(m) >0.5	11	55	66
Total	640	91	736

Overall rate of correct classification = [(629 + 55)/731] × 100 = 93.6 percent.
Overall rate of correctly predicting mortality = 55/66 × 100 = 83.3 percent.

The Malheur model did well in predicting the delayed mortality of "big" ponderosa pine (>53.3 cm). These big trees currently are being protected in U.S. Forest Service Region 6 and are of special concern to managers. Both the development and the validation stands contained big ponderosa pine. The validation stands contained 522 big trees of which 23 died; the Malheur model predicted that 25 big trees would die. The largest tree in the validation data set was 208.3 cm dbh. The model development data set contained 213 big trees of which 15 died. A classification table was prepared for the combined big tree data (table 7). The overall rate of correct classification and the overall rate of correctly predicting mortality were 95.2 percent and 66.6 percent, respectively. The big trees were not given any special treatment or protection during either the development or the validation burns (n = 22 burns) yet the mortality rate of big trees was 5.2 percent (n = 735) while the mortality rate of all sample trees was 14 percent (n = 6,652).

The Malheur model can be used to determine the probability of fire-caused mortality of big ponderosa pine.

Table 7—Classification table for large ponderosa pine (over 53.3 cm d.b.h.) based on the Malheur model logistic regression using a cutoff of 0.5 probability of mortality

	Observed		
Predicted	**Alive**	**Dead**	**Total**
Alive *P*(m) <0.5	694	32	726
Dead *P*(m) >0.5	3	6	9
Total	697	38	735

Overall rate of correct classification = [(694 + 6)/735] × 100 = 95.2 percent.
Overall rate of correctly predicting mortality = 6/9 × 100 = 66.6 percent.
There were 735 big (over 53.3 cm d.b.h) trees in the original and the validation data sets, of which 38 died; the two-factor model predicted 33.5 would die.

Ponderosa pine that have had all needles consumed or scorched but have not had significant bark consumption have a small but real probability of survival. In the validation data set (n = 3,237), 162 trees had all needles consumed or scorched; of these, 95 regreened (new needles formed) within a season of the burn, and 14 were still living 3 years later. In the development data set, 278 trees had all needles consumed or scorched; of these, 30 regreened within a season and 10 were still living 8 years later.

Conclusions

1. There is good agreement between the delayed mortality predicted by the Malheur model and the mortality observed 3 years following the burn in the 10 validation stands.
2. The geographic area of inference for using the Malheur model has been expanded north of the development stands and south into northern California.
3. The Malheur model can be used to determine probability of fire-caused delayed mortality in individual trees regardless of whether the fire is a prescribed fire or a wildfire.
4. The Malheur model can be used to determine the probability of fire-caused mortality of big ponderosa pine.
5. The observed proportion of big ponderosa pine killed by fire was about 5 percent.

Epilogue

An additional validation study was begun in summer 2007 to broadly sample burns in eastern Washington and Oregon. The sample burns are expected to include equal numbers of wildfires and prescribed burns. Each ponderosa pine stand will be evaluated by using both conventional height-measurement instruments as well as the simple proportional system shown on the field guide.

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