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Evaluation of a post-fire tree mortality model for western USA conifers

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Abstract. Accurately predicting fire-caused mortality is essential to developing prescribed fire burn plans and post-fire salvage marking guidelines. The mortality model included in the commonly used USA fire behaviour and effects models, the First Order Fire Effects Model (FOFEM), BehavePlus, and the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS), has not been tested with independently collected post-fire tree mortality data. The model predicts mortality for a wide range of conifer species based on crown scorch and species-specific bark thickness. We evaluated the mortality model on 13 western USA conifers: subalpine fir, red fir, white fir, Douglas-fir, incense cedar, western larch, western hemlock, Engelmann spruce, whitebark pine, lodgepole pine, ponderosa pine, Jeffrey pine, and sugar pine. Predicted stand-level mortality was within ±20% of observed mortality for all species except incense cedar, western larch, red fir, and western hemlock. Individual tree mortality prediction was most accurate for subalpine fir, incense cedar, ponderosa pine, and Jeffrey pine. Evaluation of the model provides managers with an accuracy assessment for estimating the probability of mortality for the majority of western USA conifers when using the mortality model to make land management decisions.[A]

Additional keywords: BehavePlus, FFE-FVS, FOFEM, model accuracy, prescription, salvage, tree survival.

Introduction

Accurate prediction of post-fire tree mortality is critical for making sound land management decisions such as developing prescribed burning prescriptions and post-fire salvage marking guidelines. Most post-fire logistic regression mortality models are species-specific and incorporate morphological injury variables as well as tree attributes (i.e. size, bark thickness). Most models have been developed for western United States (USA) conifers (Peterson and Arbaugh 1989; Saveland *et al.* 1990; Harrington 1993; Regelbrugge and Conard 1993; Mutch and Parsons 1998; Stephens and Finney 2002; McHugh and Kolb 2003; Keyser *et al.* 2006; Sieg *et al.* 2006; Thies *et al.* 2006; Hood *et al.* 2007; Hood and Bentz 2007). Logistic regression mortality models have also been developed for some species in Canadian (Beverly and Martell 2003; Hély *et al.* 2003), European (Rigolot 2004), and South American (Barlow *et al.* 2003) forests.

Managers in the USA often use the mortality model included in the First Order Fire Effects Model (FOFEM v. 5.0), BehavePlus (v. 3.0), and the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS, Suppose v. 1.19A) to evaluate fuel treatment and silvicultural prescription options (Reinhardt *et al.* 1997; Andrews *et al.* 2003; Reinhardt and Crookston 2003). The mortality model form is the same in all three of the fire behaviour and effects software programs.

Ryan and Reinhardt (1988) developed the original logistic regression mortality model used in today's USA fire behaviour and effects models. Ryan and Amman (1994) updated the original model to the form currently used in FFE-FVS, FOFEM, and BehavePlus. The Ryan and Amman mortality model (R-A model) includes a bark thickness term based on species and diameter at breast height (DBH), allowing the user to calculate predicted mortality using one model for a wide range of species. Besides bark thickness, the R-A model's only other input is percentage crown volume scorched, an easily and quickly determined fire-injury variable.

The R-A model uses percentage crown volume scorched and bark thickness to predict 3-year post-fire tree mortality. The model predicts that probability of mortality declines with increasing tree size and increases with increasing crown scorch in the form:

$$P_{\mathrm{m}} = 1/(1 + \exp(-1.941 + 6.316(1 - \exp(-0.3937BT)) - 0.000535(CVS^2))) \qquad (1)$$

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where P_m, probability of mortality; BT, bark thickness (cm); CVS, percentage of pre-fire crown volume scorched.

FFE-FVS, FOFEM, and BehavePlus are used to predict fire behaviour and effects based on topography, fuels, weather, and stand conditions. For comparing silvicultural prescriptions and creating prescribed burn plans, either the expected flame length or scorch height is used to estimate crown length scorched (Van Wagner 1973; Reinhardt and Ryan 1988). The scorch variable used in the R-A model is the percentage of pre-fire needle volume killed in the crown and assumes that needle kill and bud kill are equal. The crown volume scorched variable is calculated using the form:

$$CVS = 100CLS(2CL - CLS/CL^2) \tag{2}$$

where CVS, crown volume scorched (%); CLS, crown length scorched (m); CL, crown length (m).

FFE-FVS, FOFEM, and BehavePlus use a set of standardised bark thickness equations where bark thickness is assumed to have a liner relationship to DBH in the form:

$$BT = v(DBH) \tag{3}$$

where BT, bark thickness (cm); v, species specific multiplier; DBH, diameter at breast height (cm).

The species-specific multipliers, v, are modified from the equations used in the base FVS model. They are scaled to reflect increasing bark thickness and fire tolerance (Lutes 2001; Reinhardt and Crookston 2003).

Although the R-A model is now widely used as a silvicultural tool in the western USA, it was developed from a relatively small sample of seven western coniferous species ($n = 2356$) and only from prescribed fires in the Pacific north-west and northern Rockies (see Ryan and Reinhardt 1988 for site descriptions). The predictive accuracy of the model has not been assessed for fires outside the original study's geographic area, for wildfires, or for other tree species except ponderosa pine (*Pinus ponderosa* P. & C. Lawson) (Weatherby *et al.* 1994; Finney 1999). The species included in the original model development were Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco), western larch (*Larix occidentalis* Nutt.), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), lodgepole pine (*Pinus contorta* Dougl. ex Loud.), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), western red cedar (*Thuja plicata* Donn ex D. Don), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.).

We evaluated the R-A model using fire-injury data amassed from numerous post-fire tree mortality studies across the western USA in order to assess (1) individual tree predictive accuracy; (2) stand-level predictive accuracy; and (3) differences in predictive accuracies among fires by species. Individual tree accuracy is useful for developing post-fire salvage guidelines to mark individual trees for harvest based on a predicted probability that the trees will soon die (USDA Forest Service 1996*a*, 1996*b*; Smith and Cluck 2007). Stand-level accuracy is useful for developing prescribed fire burn plans to predict mortality levels in order to achieve desired future stand structures and for comparing silvicultural or fuel treatments.

Accuracy for prediction of mortality 3 years after burning was assessed for all species used in the development of the original model, with the exception of western red cedar because independent fire injury data were not available. In addition, we assessed model accuracy for white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.), red fir (*A. magnifica* A. Murr.), incense cedar (*Calocedrus decurrens* (Torr.) Florin), whitebark pine (*Pinus albicaulis* Engelm.), Jeffrey pine (*P. jeffreyi* Grev. & Balf.), ponderosa pine, and sugar pine (*P. lambertiana* Dougl.).

Methods

Study sites

We pooled the 14 803 sample trees used in the current analysis from numerous fire-injury studies collected for 13 coniferous species from 21 fires in Arizona, California, Idaho, Montana, and Wyoming (Table 1). Three year post-fire tree mortality was used for all fires. Fires occurred between 1982 and 2002 and included both prescribed fires and wildfires. Sample trees cover a broad range of diameters and crown injury (Table 2). Species are listed by order of increasing bark thickness for all figures and tables. Although some data used for the model validation are unpublished, most of the fires have been described elsewhere (Table 1).

Measurements

Crown scorch and DBH, the two variables required to test the R-A model, were assessed on all trees within 1 year after fire. Percentage crown volume scorched was estimated for all species except red fir and sugar pine. For these species, crown length and crown length scorched were measured and percentage crown volume scorched was calculated using Eqn 2. Both crown volume scorched and crown length scorched values are based on the portions of the pre-fire crown that were either scorched or consumed.

The R-A model does not differentiate between crown needle scorch and crown bud kill. Although these variables are approximately equal for most species, the difference can be substantial for some species such as ponderosa pine, Jeffrey pine, and western larch (Wagener 1961; Dieterich 1979; Ryan and Reinhardt 1988; Hood *et al.* 2007). Both crown bud kill and crown needle scorch were assessed on 5635 ponderosa and Jeffrey pine trees. Crown bud kill equals the percentage of pre-fire crown volume where buds were killed either by heated air (scorched) or direct flame contact (consumed). Crown scorch equals the percentage of the pre-fire crown volume where needles were either scorched or consumed and could include areas with live and dead buds. We tested model accuracy using both crown injury variables for these trees. We excluded the Dauber, Side, and Bridger-Knoll fires in Arizona from the crown kill analysis because these trees had no crown bud kill data.

We calculated the bark thickness from the DBH measurements using the species-specific equations in Reinhardt and Crookston (2003) (Eqn 3). Because of morphological similarities, the ponderosa and Jeffrey pines from fires in California were grouped into one yellow pine category during data collection. Therefore, we used the ponderosa pine equation to calculate bark thickness for all yellow pines.

Data analysis

We used general linear mixed models (GLMM) to test for differences in crown volume scorched and DBH between live

Table 1. Summary of fire data used to test the Ryan and Amman (R-A) mortality model

Species: LP, lodgepole pine; WP, whitebark pine; ES, Engelmann spruce; RF, red fir; WH, western hemlock; SF, subalpine fir; WF, white fir; IC, incense cedar; JP, Jeffrey pine; PP, ponderosa pine; DF, Douglas-fir; WL, western larch; SP, sugar pine

Fire name	State	Fire type	Month, year	Species	No. trees	Reference
Dauber	Arizona	Prescribed	Sept. 1995	PP	222	McHugh and Kolb 2003
Bridger-Knoll	Arizona	Wild	June 1996	PP	833	McHugh and Kolb 2003
Side	Arizona	Wild	May 1996	PP	312	McHugh and Kolb 2003
Rodeo-Chediski	Arizona	Wild	June 2002	PP	698	S. Hood, unpubl. data[A]
Barkley	California	Wild	Sept. 1994	SP	20	Smith 1995
Bucks	California	Wild	Aug. 1999	RF, SP	127	Hood *et al.* 2007
Storrie	California	Wild	Aug. 2000	RF	97	Hood *et al.* 2007
Star	California	Wild	Aug. 2001	SP	74	Hood *et al.* 2007
Cone	California	Wild	Sept. 2002	JP, PP	1064	Hood *et al.* 2007
McNally	California	Wild	July 2002	WF, IC, JP, PP	3754	Hood *et al.* 2007
Oops	Idaho	Wild	Oct. 1982	DF, WH	151	K. Ryan, unpubl. data[A]
Air Patrol	Montana	Wild	Aug. 1988	PP	505	Finney 1999
Brewer	Montana	Wild	June 1988	PP	627	Finney 1999
Early Bird	Montana	Wild	June 1988	PP	616	Finney 1999
Canyon Creek	Montana	Wild	Sept. 1988	WL	69	K. Ryan, unpubl. data[A]
Mussigbrod	Montana	Wild	Aug. 2000	SF, WP, LP, ES, DF	1102	Hood and Bentz 2007
Moose	Montana	Wild	Aug. 2001	SF, WL, WP, LP, ES, DF	1266	Hood and Bentz 2007
Lubrecht	Montana	Prescribed	April 2002	WL, LP, PP, DF	1696	Gundale *et al.* 2005
Tenderfoot	Montana	Prescribed	Sept. 2002	SF, WP, LP, ES	961	Hardy *et al.* 2006
Yellowstone	Wyoming	Wild	June 1988	SF, LP, ES, DF	310	Ryan and Amman 1994
Green Knoll	Wyoming	Wild	Aug. 2001	SF, LP, DF	299	Hood and Bentz 2007

[A] Data on file at Rocky Mountain Research Station, Fire Sciences Laboratory, Missoula, MT, USA.

Table 2. Mean, standard error, median, and range of crown scorch and diameter at breast height (DBH) by species of trees used to test the Ryan and Amman (R-A) mortality model

Species are listed in order of increasing bark thickness using bark thickness equations in Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS)

Species	No. trees	Crown scorch (%)			DBH (cm)		
		Mean ± s.e.	Median	Range	Mean ± s.e.	Median	Range
Lodgepole pine	1550	29 ± 1.0	5	0–100	21.2 ± 0.2	19.8	10.2–56.4
Whitebark pine	154	27 ± 3.0	5	0–100	23.0 ± 0.6	22.6	12.4–58.9
Engelmann spruce	266	36 ± 2.1	25	0–100	32.5 ± 0.9	30.2	10.4–85.1
Red fir	209	60 ± 2.2	71	0–99	42.1 ± 1.2	38.9	15.2–104.6
Western hemlock	147	22 ± 2.3	10	0–100	27.3 ± 0.6	27.2	13.0–44.2
Subalpine fir	905	68 ± 1.3	90	0–100	19.8 ± 0.3	17.8	10.2–75.2
White fir	1880	71 ± 0.6	75	0–95	60.3 ± 0.5	57.2	25.4–152.7
Incense cedar	788	44 ± 1.2	50	0–95	51.6 ± 0.9	43.7	25.4–166.4
Yellow pine[A]	7004	58 ± 0.5	70	0–100	41.7 ± 0.3	35.1	6.3–178.1
Douglas-fir	1482	35 ± 0.9	20	0–100	33.2 ± 0.4	30.0	10.2–105.4
Western larch	309	34 ± 2.2	10	0–100	35.8 ± 0.8	35	10.2–98.8
Sugar pine	109	71 ± 2.7	81	0–100	67.7 ± 1.7	68.8	26.2–106.4

[A] Includes ponderosa and Jeffrey pine.

and dead trees, including fire as a random effect when sample trees were distributed across multiple fires (Littell *et al.* 1996). When sample trees came from only one fire, we used Wilcoxon–Mann–Whitney tests to test for differences between live and dead trees. P-values less than or equal to 0.05 in the GLMM and Wilcoxon–Mann–Whitney tests were considered statistically significant.

We calculated the predicted probability of mortality (P_m) for all trees ($n = 14\,803$) using the R-A model (Eqn 1). Predictive accuracy of the R-A model by species was then assessed at the individual tree level and stand level. We evaluated individual tree accuracy using classification tables and Receiver Operator Characteristic (ROC) curves. Stand-level mortality was assessed by comparing actual *v.* predicted mortality across 0.1 P_m classes.

Classification tables allow the user to determine classification accuracy of a model based on the selected P_m. Trees with values above the selected cutoff probability are classified as dead, whereas trees below the cutoff probability are classified as live. The selected cutoff level determines the model accuracy. Studies have typically reported model accuracy based on either P_m

equal to 0.5 or 0.6 (Ryan and Reinhardt 1988; Regelbrugge and Conard 1993; Keyser *et al*. 2006; Thies *et al*. 2006). The classification data presented for the present study display the percentage of trees that were correctly predicted as live and dead (total correct), the percentage of trees the model predicted to die and that were observed dead (correctly predicted mortality), and the percentage of trees the model predicted to live and that were observed live (correctly predicted survival) from P_m 0.1 to 0.9.

Data from the classification tables are shown as figures for ease of interpretation and comparison by species. High correctly predicted mortality values indicate the majority of trees predicted to die did so within 3 years after fire. Conversely, low correctly predicted mortality values indicate many trees predicted to die survived for at least 3 years after fire (mortality overpredicted). High correctly predicted survival values mean that the majority of trees predicted to live survived at least 3 years after fire. Alternatively, low correctly predicted survival values mean that many trees predicted to live died within 3 years (mortality underpredicted).

To see how well the model predicts individual tree mortality, both correctly predicted survival and mortality must be examined. These are not the inverse of each other as one may first assume. For example, the correctly predicted mortality rate may be very high because a higher, conservative cutoff point was chosen. In this case, the majority of trees predicted to die do in fact die. However, because of this higher cutoff point, many trees predicted to survive end up dying. This lowers the correctly predicted survival rates.

Saveland and Neuenschwander (1990) first advocated the use of ROC curves for tree mortality model evaluation. Several authors since have used ROC methodology to evaluate logistic regression models (Regelbrugge and Conard 1993; Stephens and Finney 2002; Beverly and Martell 2003; McHugh and Kolb 2003; Rigolot 2004; Keyser *et al*. 2006; Sieg *et al*. 2006; Thies *et al*. 2006; Hood *et al*. 2007; Hood and Bentz 2007). The ROC curve is a plot of the probability of a true positive prediction (tree classified and observed dead) *v*. the probability of a false positive prediction (tree classified as dead when it is alive) across the continuous P_m cutoff ranges from 0 to 1 (Saveland and Neuenschwander 1990; Bradley 1996). The ROC reflects the accuracy of the model in classifying live and dead trees, with a value of 0.5 being no better than chance and 1.0 indicating a perfect fit. Hosmer and Lemeshow (2000) report ROC values equal to 0.5 suggest no discrimination from a 50–50 chance, and values between 0.7 and 0.8 are acceptable discrimination, between 0.8 and 0.9 are excellent discrimination, and greater than 0.9 are considered outstanding discrimination. Swets (1996) used similar guidelines.

When using the model to predict stand-level mortality, the calculated P_m equals the percentage of the trees in a stand that are predicted to die by tree species and size class. To test stand-level model accuracy, we grouped trees into 0.1 P_m classes by species after calculating the P_m for each tree. Predicted mortality equalled the respective P_m class (e.g. P_m class 0.8 equalled 80% predicted mortality). We then calculated the actual percentage of trees in each P_m group that died (observed mortality). We compared actual *v*. predicted group mortality by subtracting the predicted mortality from the observed mortality. Positive differences reveal where the R-A model overpredicts stand-level post-fire mortality, whereas negative differences indicate where stand-level post-fire mortality is underpredicted. We calculated overall stand-level accuracy by summing the predicted mortality of each group and subtracting the summed value from the total observed mortality.

We used this process for all species except Engelmann spruce. FFE-FVS, FOFEM, and BehavePlus predict 80% post-fire spruce mortality, regardless of injury or size class. The Engelmann spruce used in the R-A model development had very high observed mortality, regardless of crown scorch level. The model developers chose the 80% mortality 'floor' for the software packages so that the predictions would better match the observations (E. Reinhardt, pers. comm.). Therefore, we compared observed mortality *v*. the predicted 80% mortality for Engelmann spruce.

Model accuracy for predicting individual tree and stand-level mortality was compared among different fires for lodgepole pine, Engelmann spruce, subalpine fir, yellow pine, and Douglas-fir using the same methods as described above, as these species were sampled from multiple fires. For these species, we only used sites that included more than 100 sample trees.

Results

Dead trees had significantly higher crown scorch than live trees for all species tested (Table 3). The relationship of DBH between live and dead trees was not as clear. Dead trees had significantly smaller diameters than live trees for lodgepole pine, western hemlock, yellow pine, Douglas-fir, and western larch. However, there were no significant differences in DBH between live and dead trees for whitebark pine, Engelmann spruce, red fir, subalpine fir, incense cedar, and sugar pine. Dead white fir, yellow pines from the McNally fire, and Douglas-fir from the Green Knoll fire had significantly larger diameters than live trees.

Individual tree mortality

The model most accurately classified subalpine fir (ROC = 0.91), followed closely by incense cedar (ROC = 0.88) (Table 3). Red fir (ROC = 0.65) and Engelmann spruce (ROC = 0.69) were the least accurately classified. Comparisons of ROC values for individual fires showed large fluctuations in accuracy. In the yellow pine group, ROC values ranged from a high of 0.93 for the Bridger-Knoll fire to a low of 0.68 for the McNally fire. Douglas-fir ROC values ranged from a high of 0.88 for the Lubrecht fire to a low of 0.64 for the Green Knoll fire.

Individual tree survival was most accurately predicted for red fir, incense cedar, and western larch, whereas individual tree mortality accuracy was the lowest (Fig. 1*d*, *h*, *k*). Mortality was very low (<17%) for these species (Table 3). When observed post-fire mortality was very low, the model overpredicted mortality, but predicted survival very accurately. Large fluctuations in correctly predicted survival for lodgepole and whitebark pine were due to the model predicting very few trees to survive (Fig. 1*a*, *b*). In this situation, a few misclassified trees caused large differences in the percentage of correctly classified trees.

Accuracy of predicted individual tree mortality generally increased with increasing P_m (Fig. 1). The exception was sugar pine. This again was due to the model predicting very few trees to die. At $P_m = 0.9$, only two trees were predicted to die and of

Table 3. Summary statistics of trees by species and fire used to evaluate the Ryan and Amman (R-A) mortality model and predictive accuracy of the R-A mortality model

Statistics are only reported for individual fires if more than 100 trees were sampled. Species are listed in order of increasing bark thickness using bark thickness equations in Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS)

Species	No. trees	Average DBH (cm)			Average crown scorch (%)			Observed dead (%)	R-A predicted dead (%)	Predicted – observed (%)	ROC
		Live	Dead	*P*-value	Live	Dead	*P*-value				
Lodgepole pine	1550	24.7	22.4	<0.001	12	41	<0.001	62	69	+7	0.74
Mussigbrod	527	21.9	18.9	<0.001	5	14	0.002	53	65	+11	0.68
Tenderfoot	767	22.7	20.2	<0.001	13	57	<0.001	67	73	+6	0.79
Yellowstone	151	24.4	25.3	0.615	1	30	<0.001	58	62	+4	0.67
Whitebark pine	154	24.0	22.0	0.087	30	58	<0.001	49	66	+17	0.75
Engelmann spruce	266	32.1	31.8	0.920	25	55	<0.001	74	80	+6	0.69
Moose	118	44.3	30.8	0.051	8	40	0.002	88	80	−8	0.79
Mussigbrod	105	31.0	36.6	0.147	11	36	<0.001	54	80	+26	0.62
Red fir	209	43.5	37.9	0.090	56	76	0.008	17	66	+48	0.65
Western hemlock	147	32.8	25.2	<0.001	10	27	0.001	71	47	−24	0.79
Subalpine fir	905	21.7	21.3	0.550	16	77	<0.001	82	79	−3	0.91
Moose	453	23.8	20.1	0.043	36	83	<0.001	95	84	−11	0.90
Mussigbrod	205	20.0	20.4	0.580	14	59	<0.001	67	71	+4	0.83
Tenderfoot	172	16.9	16.4	0.833	5	86	<0.001	60	74	+14	0.92
White fir	1880	56.3	63.3	<0.001	54	84	<0.001	57	59	+2	0.79
Incense cedar	788	52.2	47.6	0.077	37	86	<0.001	13	35	+22	0.88
Yellow pine[A]	7004	39.1	36.6	<0.001	42	78	<0.001	43	53	+10	0.82
Air Patrol	505	28.8	27.9	0.102	42	71	<0.001	58	59	+1	0.74
Brewer	627	24.7	21.9	<0.001	49	75	<0.001	29	62	+33	0.75
Bridger-Knoll	833	51.7	51.6	0.920	22	90	<0.001	14	23	+9	0.93
Cone	1064	46.1	40.7	<0.001	75	98	<0.001	56	77	+21	0.85
Dauber	222	25.1	20.3	<0.001	37	85	<0.001	18	55	+37	0.92
Early Bird	616	32.7	27.3	<0.001	29	72	<0.001	33	42	+10	0.85
Lubrecht	1041	26.0	20.0	<0.001	13	66	<0.001	11	35	+25	0.85
McNally	1086	73.1	81.9	<0.001	70	87	<0.001	84	57	−27	0.68
Rodeo-Chediski	698	36.3	31.3	<0.001	45	92	<0.001	65	69	+4	0.86
Side	312	41.8	36.4	0.007	52	93	<0.001	32	57	+24	0.85
Douglas-fir	1482	39.0	34.5	<0.001	15	60	<0.001	39	39	0	0.74
Green Knoll	218	39.5	47.0	0.005	9	46	<0.001	68	32	−36	0.64
Lubrecht	549	24.8	20.3	<0.001	16	70	<0.001	21	43	+21	0.88
Moose	468	42.5	33.1	<0.001	24	69	<0.001	47	40	−7	0.83
Mussigbrod	118	32.1	25.5	0.012	10	36	<0.001	28	33	+5	0.75
Yellowstone	125	40.5	37.8	0.053	22	67	<0.001	52	40	−12	0.76
Western larch	309	33.9	25.1	0.001	37	67	<0.001	12	37	+25	0.77
Sugar pine	109	57.9	65.2	0.195	51	68	0.018	62	44	−18	0.79

[A] Includes ponderosa and Jeffrey pine.

these, one survived. At the upper P_{m} levels, the model predicted individual tree mortality with greater than 80% accuracy for all species except red fir, incense cedar, and western larch (Fig. 1).

With the exception of red fir, those species with thinner bark – lodgepole pine, whitebark pine, Engelmann spruce, western hemlock, and subalpine fir – tended to have low correctly predicted survival rates (Fig. 1). When correctly predicted survival is low, many of the trees the model predicts to live actually die and individual tree mortality is underpredicted. This was especially true for Engelmann spruce, western hemlock, and subalpine fir. For these three species, observed mortality 3 years after fire was greater than 70%. The majority of western hemlock trees (72%) and Engelmann spruce trees (86%) with scorch greater than 5% died.

The model correctly predicted surviving yellow pine trees with greater than 80% accuracy for all fires, except Air Patrol and McNally, across all P_{m} cutoffs. Survival accuracy was very poor (<40% across all cutoffs) for the McNally fire. Yellow pine mortality was predicted more accurately at the upper P_{m} cutoffs for all fires. At a P_{m} cutoff of 0.9, the model correctly predicted mortality within 80% accuracy for all fires except Brewer, Dauber, and Side.

Douglas-fir survival was predicted most accurately on the Lubrecht fire (>90% across all cutoffs) and least accurately on the Green Knoll fire (~40% across all cutoffs). The model was most accurate in predicting both survival and mortality at the upper cutoffs. The model predicted lodgepole pine, Engelmann spruce, and subalpine fir mortality with greater accuracy than survival for all individual fires tested. Survival prediction accuracy was less than 30% for spruce on the Moose fire.

Model accuracy increased slightly when crown bud kill values were used instead of crown scorch to calculate yellow pine

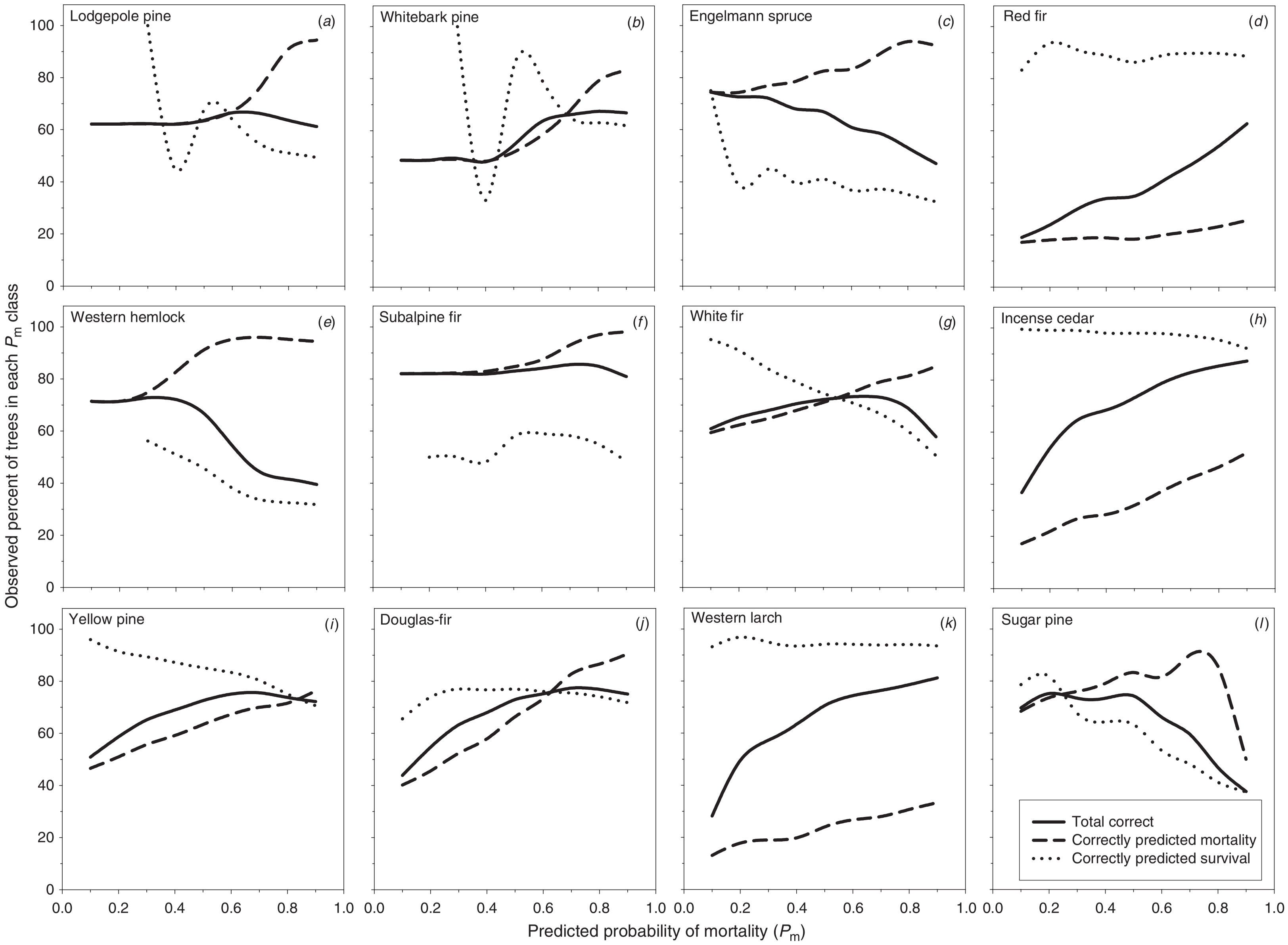

Fig. 1. Classification accuracy of (*a*) lodgepole pine, (*b*) whitebark pine, (*c*) Engelmann spruce, (*d*) red fir, (*e*) western hemlock, (*f*) subalpine fir, (*g*) white fir, (*h*) incense cedar, (*i*) yellow pine (ponderosa and Jeffrey pine), (*j*) Douglas-fir, (*k*) western larch, and (*l*) sugar pine using the Ryan and Amman (R-A) mortality model to predict individual tree mortality. Species are arranged in order of increasing bark thickness using bark thickness equations in the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS). Large fluctuations in accuracy can result when few trees are predicted to either live or die (*a*, *b*, *c* and *l*). For example, when lodgepole pine $P_m = 0.3$, two trees were predicted to live and both lived. At $P_m = 0.4$, nine lodgepole trees were predicted to live, but five died. When sugar pine $P_m = 0.9$, two trees were predicted to die, but one lived.

probability of mortality (ROC = 0.81 *v.* 0.79). When kill was used in the model, no surviving trees over 75-cm DBH were predicted to die. Rather, mortality was underpredicted for the larger trees. Mortality was overpredicted for trees less than 75 cm, especially for trees between 13-cm and 50-cm DBH with crown kill levels between 30 and 70% and scorch levels greater than 75%.

Stand-level mortality

Overall stand-level mortality was most overpredicted for red fir, incense cedar, and western larch (Table 3). Observed mortality was also the lowest for these three species, and the majority of dead trees had greater than 95% scorch. Western hemlock and sugar pine mortality were most underpredicted. Overall stand-level mortality was predicted extremely accurately for subalpine fir, white fir, and Douglas-fir (Table 3).

The model overpredicted stand-level mortality across nearly all P_m levels for all species except western hemlock, subalpine fir, white fir, and sugar pine (Fig. 2). White fir stand-level mortality was predicted within 10% for all P_m levels (Fig. 2*g*). There was no clear trend in over- or underprediction for subalpine fir across all P_m levels (Fig. 2*f*). Western hemlock and sugar pine mortality were underpredicted (Fig. 2*e*, *l*). Douglas-fir mortality was also underpredicted when P_m values were less than 0.2 (Fig. 2*j*).

When differences in individual fires were examined, the model overpredicted yellow pine mortality across all P_m levels for all fires except the McNally and Air Patrol fires. Mortality on the Air Patrol fire was underpredicted for P_m levels less than 0.4 and was overpredicted above this level. Mortality on the McNally fire was underpredicted across all P_m levels. The Lubrecht fire was the only fire where Douglas-fir mortality was overpredicted across all P_m levels. Douglas-fir mortality was most underpredicted on the Green Knoll and Yellowstone fires (Table 3). Lodgepole pine, Engelmann spruce, and subalpine fir mortality was overpredicted for all fires except the Moose fire. For this fire, Engelmann spruce and subalpine fir were underpredicted and lodgepole pine was not sampled (Table 3).

Discussion

Mortality prediction for red fir, incense cedar, and western larch was particularly poor, whereas survival prediction was most accurate. The overprediction of mortality suggests that these species can survive higher levels of crown scorch than the other species tested. The low accuracy of red fir could be due to the calculated percentage crown volume scorch values based on crown length scorched measurements (Eqn 2). However, it is most likely due to the low bark thickness factor given to red fir. The bark of young red fir trees is thin, but becomes thick, roughly fissured, and fire-resistant with age (Cope 1993). Stephens and Finney (2002) reported that incense cedar can survive high levels of crown scorch and Regelbrugge and Conard (1993) concluded that incense cedar could survive higher relative bark char heights than ponderosa pine. Western larch is considered one of the most fire-tolerant western USA species (Flint 1925; Smith and Fisher 1997). It is unique among the western USA conifers because it is deciduous. It also has extremely thick bark and woody structures around the buds that protect them from heat injury (Ryan 1982*a*; Peterson and Ryan 1986). Because of these features, crown kill would likely be a more appropriate indicator of actual crown injury than crown scorch. The western larch trees used in the present study to test the model had higher crown scorch (34%; Table 2) than the larch trees used for original model development (15%; Ryan and Reinhardt 1988). This discrepancy could also explain differences in reported model predictive accuracy between the original Ryan and Reinhardt (1988) study and the current study.

Most misclassified surviving yellow pine trees had high crown scorch, leading to lower correctly predicted mortality rates and therefore, an overprediction of mortality. This trend was across all size classes. This is likely due to the ability of yellow pine to recover from high levels of scorch if crown kill is low (Wagener 1961; Harrington 1993). Crown scorch averaged 27% higher than crown kill for false positive trees (predicted to die but lived, cutoff = 0.5). FFE-FVS, FOFEM, and BehavePlus predict scorch height based on Van Wagner's scorch height model (1973). This model works for the majority of species where scorch and kill are approximately equal. Currently, the models are not able to predict both crown scorch and kill for the few species where these values can differ, such as western larch, ponderosa pine, and Jeffrey pine. When available, crown kill estimates should be used in place of crown scorch estimates to predict P_m for these species.

Most dead yellow pine trees that were predicted to live (false negatives) were larger than 75-cm DBH. Yellow pines on the McNally fire were the largest in the study and dead trees on this fire had larger diameters than live trees (Table 3). This suggests that other factors not accounted for in the model, such as stem or root injury, bark beetle attacks, or post-fire environmental conditions, contributed to tree death.

Bole char was a significant factor in predicting mortality in the Bridger, Side, and Dauber fires (McHugh and Kolb 2003). Post-fire insect attacks also contributed to ponderosa pine mortality in these fires, mostly from *Ips* species and *Dendroctonus* species (McHugh *et al.* 2003). Cambium kill and the presence of red turpentine beetle (*Dendroctonus valens*) were also significant variables influencing yellow pine mortality in the Cone and McNally fires (Hood *et al.* 2007). Although red turpentine beetles are not normally considered a direct cause of tree mortality, they can predispose trees to fatal attacks from other bark beetles (Bradley and Tueller 2001). Perrakis and Agee (2006) also reported strong associations between western pine beetle (*D. brevicomis*) and red turpentine beetle attacks and post-fire ponderosa pine mortality.

Other explanations are that older trees cannot survive high levels of crown scorch as well as younger trees or they experienced extensive cambium injury at the bases. Older trees may have less carbohydrates available to repair injury owing to higher respiration and lower photosynthetic capacities than younger trees (Ryan *et al.* 1997; McHugh and Kolb 2003). Older ponderosa and Jeffrey pine trees may have deep duff accumulations around the tree bases. These deep duff mounds can lead to basal injury and tree mortality from smouldering combustion (Ryan and Frandsen 1991; Swezy and Agee 1991).

The range of yellow pine tree diameters from the McNally fire had little overlap with those used in the R-A model development (Ryan and Reinhardt 1988) or the other fires evaluated in the present study. This highlights the danger in extrapolating model

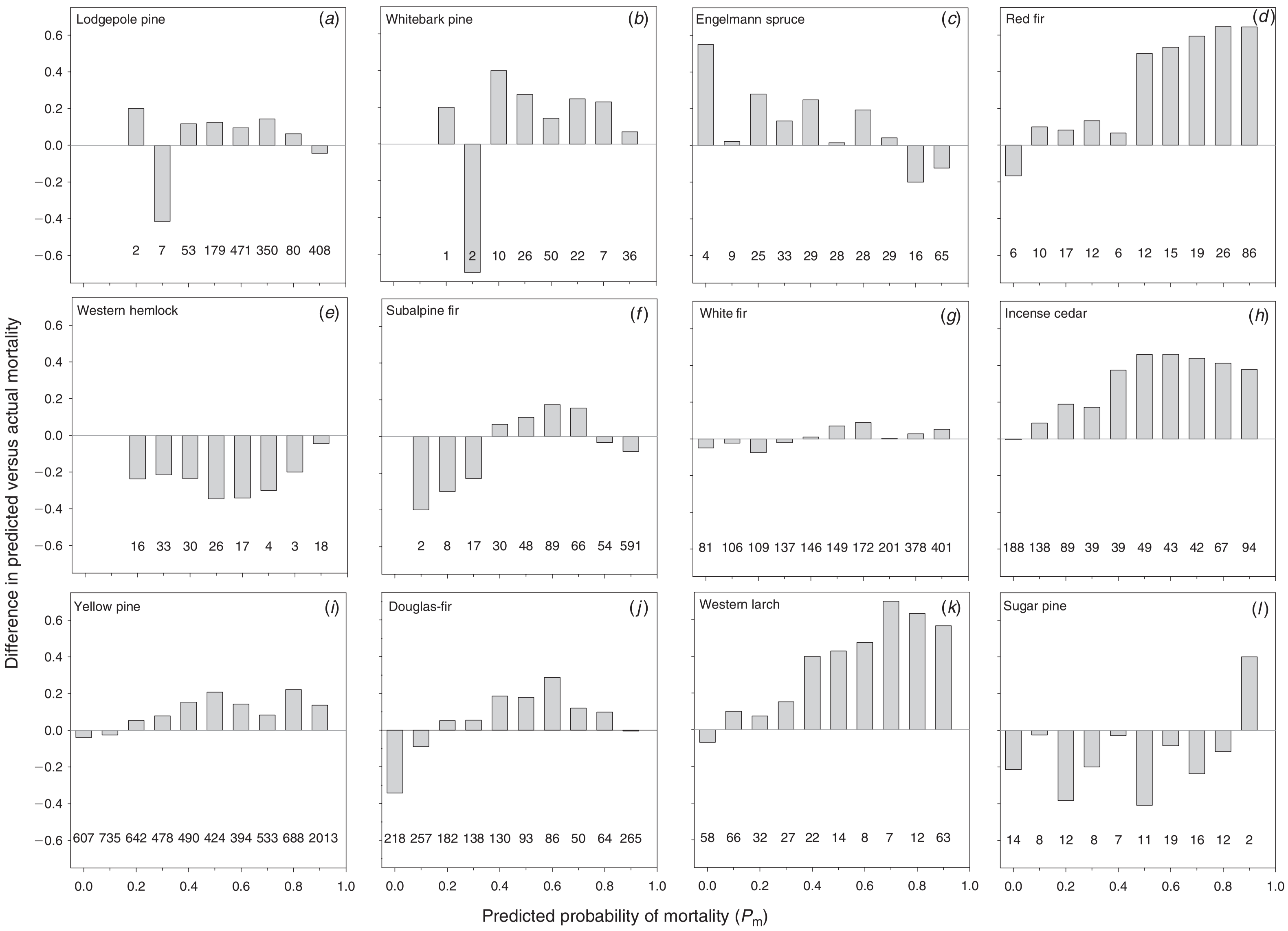

Fig. 2. Difference between predicted and observed stand-level predicted mortality for 10 predicted probability of mortality classes for (*a*) lodgepole pine, (*b*) whitebark pine, (*c*) Engelmann spruce, (*d*) red fir, (*e*) western hemlock, (*f*) subalpine fir, (*g*) white fir, (*h*) incense cedar, (*i*) yellow pine (ponderosa and Jeffrey pine), (*j*) Douglas-fir, (*k*) western larch, and (*l*) sugar pine using the Ryan and Amman (R-A) mortality model. Species are arranged in order of increasing bark thickness using bark thickness equations in the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS). Numbers at bottom of figures are numbers of trees per probability of mortality (P_m) class. Values greater than zero reflect an overprediction in stand-level mortality for that P_m class. Values less than zero reflect an underprediction.

results beyond the range of data used for development. Ninety percent of the trees used to develop the R-A model were below 68.6-cm DBH and 75% were below 51.3-cm DBH (K. Ryan, pers. comm.). Also, no ponderosa or Jeffrey pine data were used in the R-A model development. In contrast, 90% of the yellow pines in the McNally fire were above 55.1-cm DBH and 75% were above 61.5-cm DBH. Our results are only from one fire, but they suggest that the R-A model should be applied with caution in areas where the majority of trees are greater than 55-cm DBH.

The underprediction in Douglas-fir mortality at low P_m levels is likely due to Douglas-fir beetle (*Dendroctonus pseudotsugae*) attacking and killing fire-injured trees that would likely have survived if not attacked. Weatherby *et al.* (1994) also reported that the model underpredicted larger diameter Douglas-fir mortality because of Douglas-fir beetle attacks. Douglas-fir beetles were observed on all the fires containing Douglas-fir study trees and they contributed to post-fire tree mortality. On the Green Knoll, Moose, and Mussigbrod fires, Douglas-fir beetle either strip- or mass-attacked 50% of the Douglas-firs greater than 23-cm DBH, and beetles caused an estimated additional 25% post-fire mortality (Hood and Bentz 2007). Ryan and Amman (1996) reported that 71% of the Douglas-fir trees sampled in the Yellowstone fires were attacked by Douglas-fir beetle. The Lubrecht prescribed burn was the only fire where few Douglas-fir beetle attacks were observed (Hood and Bentz 2007). It was also the only fire where stand-level Douglas-fir mortality was largely overpredicted.

The Douglas-fir bark beetle is attracted to larger-diameter, fire-injured trees and can cause additional mortality among trees that would be expected to survive moderate levels of fire-injury (Rasmussen *et al.* 1996; Ryan and Amman 1996). The R-A model does not directly account for secondary mortality agents such as bark beetles. However, some mortality models include an insect attack variable (McHugh *et al.* 2003; Sieg *et al.* 2006; Hood *et al.* 2007; Hood and Bentz 2007). When bark beetles are a concern after fire, a mortality model that includes insect attacks would likely be more accurate than the R-A model.

Mortality prediction would likely be improved by incorporating a stem injury variable into the model. Ryan and Reinhardt (1988) also reported that measured cambium injury would be a better predictor of tree mortality than bark thickness. The numerous post-fire tree mortality models and guidelines that include a stem injury variable indicate this as well (Wagener 1961; Peterson and Arbaugh 1989; McHugh and Kolb 2003; Thies *et al.* 2006; Hood *et al.* 2007).

Accuracy may also be improved by using other bark thickness equations. The simplified bark thickness equations used in FOFEM, FFE-FVS, and BehavePlus warrant further research. Bark thickness may vary by site, geographic location, and height above ground (Ryan 1982*b*), and numerous bark thickness equations exist for individual species. Localised bark thickness equations may more accurately reflect a tree's natural resistance to cambium damage from fire and thus result in more accurate predictions of tree mortality.

When bark is thin, even very light charring can kill the cambium (Ryan 1982*a*). Even with low crown scorch, extensive girdling caused from the fire can result in tree death. By only basing probability of mortality on crown scorch and bark thickness, stem and root injuries are not considered. Jones *et al.* (2004) developed a stem heating model to predict cambium death from fire exposure. In the future, their model has the potential to be incorporated into the USA fire behaviour and effects models to predict cambium injury for use as an input into a mortality model that includes a stem injury variable. This application would be especially useful when planning prescribed burns and could possibly improve post-fire mortality predictions.

The data used to develop the R-A model came exclusively from prescribed fires (Ryan and Reinhardt 1988). However, there was no clear difference in model performance between the prescribed fires and wildfires evaluated here. This supports the theory that tree mortality from fire injury is related to fire intensity and fuel consumption. Intensity and consumption are usually lower in prescribed fires than wildfires, resulting in lower fire injury levels. Therefore, it seems that mortality models developed using the full range of fire injuries (low-to-high crown scorch and low-to-high cambium damage) could be applied to either prescribed fires or wildfires with equal accuracy.

Conclusions

For the current study, we examined the accuracy of a widely used USA tree mortality model on numerous western USA coniferous species over much wider geographic ranges and fire types (wildfire and prescribed fire). We evaluated the efficacy of the model in predicting mortality of several species not included in the development of the original model. Few independent evaluations of this commonly used post-fire tree mortality model have been completed before the present study (but see Weatherby *et al.* 1994; Finney 1999). This evaluation provides managers in the USA with an assessment of the model's accuracy when predicting tree mortality and survival after fire in order to better understand the strengths and weaknesses of the model.

The R-A mortality model is widely accessible to managers in the USA through several fire behaviour and effects software packages. It is easily applied to any species as long as crown scorch and DBH are known. For prescribed burn planning purposes, the model proved to be a useful and relatively accurate method for predicting stand-level post-fire tree mortality. It correctly predicted overall mortality within ±20% of the observed mortality for the majority of species tested. These species were lodgepole pine, whitebark pine, Engelmann spruce, subalpine fir, white fir, ponderosa pine, Jeffrey pine, Douglas-fir, and sugar pine. However, correctly predicted mortality was quite variable when individual fires were examined and model accuracy may be lower for some fires, as indicated by the data. Red fir, incense cedar, and western larch stand-level mortality was overpredicted. Western hemlock was the only species tested where stand-level mortality was greatly underpredicted.

Managers can expect less mortality than the model predicts when burning in incense cedar, western larch, and red fir forests. Managers can also expect higher mortality than the model predicts when planning prescribed burns in stands of western hemlock if tree boles are charred. Post-fire tree mortality predicted using FFE-FVS, FOFEM, or BehavePlus is dependant on anticipated fire behaviour. Deviations from expected fire behaviour during actual prescribed burning will result in lower stand-level tree mortality prediction accuracy.

The R-A model was less accurate for predicting individual tree mortality. Individual tree mortality predictions are used to develop post-fire salvage marking guidelines. For this purpose, other species-specific mortality models developed from individual geographic areas may be more accurate. Species-specific models often include other variables, such as stem injury and insect attacks, that can increase prediction accuracy. The species we tested that provided excellent discrimination ($\text{ROC} \geq 0.8$) were subalpine fir, incense cedar, and yellow pine. The R-A model was especially poor at classifying Engelmann spruce, red fir, and very large diameter yellow pine.

The classification figures we developed allow managers to see correctly predicted mortality and survival based on a range of P_{m} values. These figures can help managers determine if accuracy is acceptable and choose a P_{m} level for development of marking guidelines. Poor predictions of mortality will lead to cutting many trees that may have lived, but poor predictions of survival will leave many trees that may die. Managers can predict future forest stand structure by examining the accuracy of the chosen P_{m} level.

Tree mortality models can provide assistance for developing more accurate prescribed burn plans and post-fire salvage marking guidelines. However, they should be used in conjunction with other factors to meet overall management objectives. Mortality models are intended as a starting point for tree and stand assessments, and managers should augment their decision criteria after considering localised environmental and tree physiological factors such as long-term drought and associated tree stress, overall stand health and condition, bole and root injury, as well as the location of population centres and species of bark beetles and their potential effect on tree survival.

There is a need for independent evaluations of other existing tree mortality models. These models include many different variables and report accuracy in various ways, making comparisons difficult. In addition, many models were developed with localised data and likely have little inter-regional applicability. Systematic evaluations could identify limitations to individual models such as the geographic range, tree sizes, and types of fire injuries. There is also a need to contrast model accuracies with their complexity. Evaluations of this kind could greatly improve our understanding of which models should be applied in which situations and can help identify the species and situations for which accurate models do not currently exist.

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