Validation and Development of Postfire Mortality Models for Upland Forest Tree Species in the Southeastern United States

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Abstract—Fire effects and behavior models that forecast postfire tree mortality include the First Order Fire Effects Model (FOFEM), BehavePlus, and the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS). Although these models are national in scope, the underlying equations driving the prediction of fire-related mortality were derived from data obtained from coniferous forests in the Western United States. For tree species common to upland forests of the Southeastern United States, quantitative models that predict mortality following prescribed fire are lacking. Consequently, these fire effects models utilize empirical models developed for western conifers to predict mortality of eastern deciduous and conifer species. Widespread application of models built with data outside the geographic range of application, let alone across functional groups, has the potential to introduce substantial error into model forecasts and misrepresent the ecological effects of prescribed burning. In this study, we (1) validated the equations used by nationally supported fire effects models to predict postfire mortality of upland tree species in the Southeastern United States using an extensive and geographically diverse independent dataset; and (2) developed new, species-specific postfire mortality models for some of the most common conifer and deciduous broadleaved tree species/species groups in upland forests of the Southeastern United States using easily obtained tree morphological and fire effects data. By developing postfire mortality for the suite of species that comprise upland forests, and incorporating those predictive models into available fire planning tools, managers will have improved ability to predict fire effects and assess the efficacy of burn efforts guided by restoration goals and objectives.

Keywords: Central Hardwood Region, oak mortality, pine mortality, prescribed burning, restoration.

INTRODUCTION

Fire effects models that forecast the effects of prescribed burning on various ecosystem attributes include the First Order Fire Effects Model v. 6.3 (FOFEM) (Reinhardt 2003), the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Rebain 2010), and BehavePlus v. 3.0 (Andrews and others 2005). Depending on species, these programs incorporate models that predict the probability of individual tree mortality as a function of stem size, bark thickness, and crown and/or bole damage. These computer simulation models are invaluable in that they allow resource managers to assess, prior to burning, the potential effects of alternative prescribed burning prescriptions on a variety of stand-level variables including changes in structure via fire-related tree mortality. In 2014, almost 6.2 million acres of prescribed burning was conducted on forest land in the Southeastern United States (Melvin 2015). Accurate predictions of postfire mortality in the forests of this region are particularly important as restoration goals achieved via prescribed burning must consider effects on timber production and quality.

Although the aforementioned fire effects models are national in scope, the underlying equations driving the prediction of fire-related mortality were

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developed from data obtained from coniferous forests of the Western United States. Variables found to influence mortality of western conifer species such as crown damage (Ryan and Reinhardt 1988) have little predictive power for some eastern conifer species (Johansen and Wade 1987, Outcalt and Foltz 2004). Similarly, while metrics of crown damage are primary factors controlling mortality in western conifer species, they may not be the primary factor influencing mortality or topkill of deciduous broadleaved forest species (Catry and others 2010, Regelbrugge and Smith 1994), as the majority of prescribed burns in upland forests of the Southeastern United States are of low intensity (e.g., scorch/char heights <3 feet) (Hutchinson and others 2005) and rarely cause crown damage. Instead, fire effects related to cambial injury such as bole char severity rating (Kobziar and others 2006) or simple measurements of bole char height (Catry and others 2010) tend to be predictive of postfire mortality/topkill in deciduous broadleaved species.

With the exception of some species (e.g., *Pinus palustris*) (Varner and others 2007, Wang and others 2007)), quantitative models that predict mortality following prescribed fire specific to the >90 tree species found in upland southeastern forests, including both deciduous broadleaved and conifer species, are lacking. Following wildfire in the mountains of Virginia, Regelbrugge and Smith (1994) found diameter at breast height (DBH) and maximum height of bole char accurately predicted topkill of prominent upland *Quercus* species, *Acer rubrum*, *Nyssa sylvatica*, *Amelanchier arborea*, and *Carya glabra*. These equations, although some of the only fire-related mortality equations developed for deciduous broadleaved species, have not been validated for use following prescribed fire nor have they been tested for applicability outside of Virginia.

Because of the gap in knowledge regarding postfire tree mortality in forests of the Western versus Eastern United States, fire planning programs utilize empirical mortality models developed for western conifer species to predict and forecast mortality of eastern tree species. Widespread application of models built with data outside the geographic range of application and applied regardless of species has the potential to introduce substantial error into model forecasts, result in poor model performance, and misrepresent the ecological effects of prescribed burning across multiple temporal and spatial scales. In this study, we (1) validated the equations used by nationally supported fire effects models to predict postfire mortality of upland tree species in the Southeastern United States using an extensive and geographically diverse independent dataset; (2) developed new, species-specific postfire mortality models for 17 conifer and deciduous broadleaved tree species/species groups common to upland forests of the Southeastern United States using easily obtained tree morphological and fire effects data; and (3) compared accuracy of the equations produced by Ryan and Amman (1994) and Regelbrugge and Smith (1994) with the newly developed equations. Availability of species-specific individual tree postfire mortality models, such as those developed in this study, is critical to developing burn prescriptions associated with restoration efforts and forecasting the effects of prescribed burning on short- and long-term species composition in upland forests of the Southeastern United States.

METHODS

Study Sites and Data Collection

A total of 244 0.25-acre (66 feet × 164 feet) plots were established in 94 prescribed burn units throughout 13 U.S. Department of the Interior, National Park Service (NPS) lands (fig. 1) using a standardized NPS vegetation monitoring protocol (USDI National Park Service 2003). Prescribed burns ranged in size from ~1 to 5,010 acres. Most burns were completed in the late dormant to early growing season (80 percent in March and April) between 1997 and 2012. Prior to burning, individual trees were tagged, and species, status (live/dead), and stem diameter at 4.5 feet above groundline (DBH; inches) were recorded. Overstory trees (stems >5.9 inches DBH) were inventoried in the entire 0.25-acre plot, and understory trees (stems ≥1.0 inch and ≤5.9 inches DBH) were inventoried in one-quarter of the larger plot. Direct fire effects for each tagged tree were measured within approximately 1 month post-burn and included scorch height (SCOR) and char height (CHAR). Scorch height (feet) was measured from the ground level to the highest point in the crown where foliar death was evident. Because the majority of the postfire inventories were conducted during leaf-off

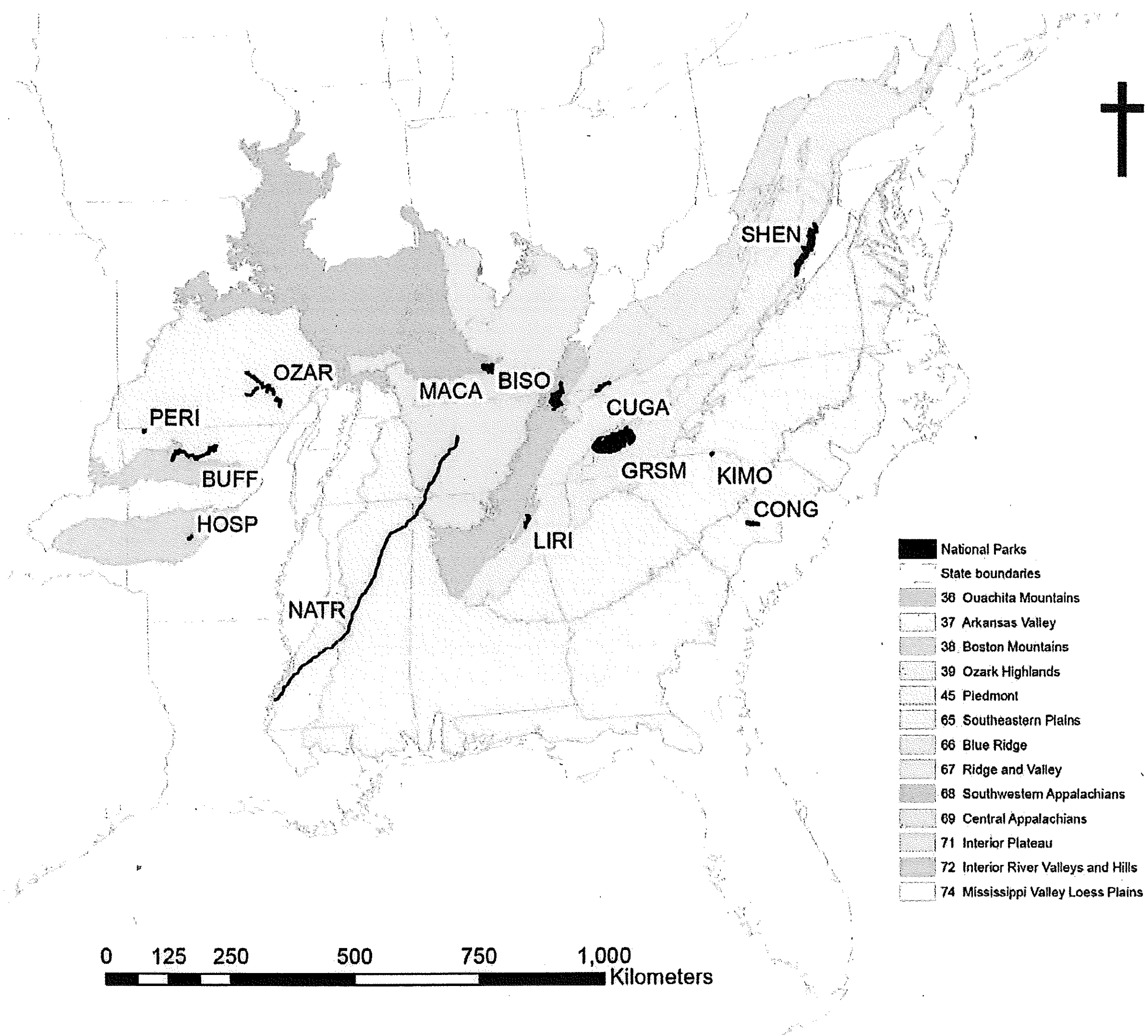

Figure 1—Map of study locations. BISO=Big South Fork National River and Recreation Area; GRSM=Great Smoky Mountains National Park; SHEN=Shenandoah National Park; CUGA=Cumberland Gap National Historic Park; MACA=Mammoth Cave National Park; KIMO=Kings Mountain National Military Park; OZAR=Ozark National Scenic Riverways; LIRI=Little River Canyon National Preserve; PERI=Pea Ridge National Military Park; CONG=Congaree National Park; NATR=Natchez Trace Parkway; HOSP=Hot Springs National Park; BUFF=Buffalo National River. Colors represent Level III Ecoregions (Omernik 1987).

(i.e., dormant season), SCOR measurements were obtained only for those deciduous broadleaved individuals possessing foliage. Char height (feet) was measured from the ground level to the highest point on the bole where char or scorch was evident regardless of slope (e.g., uphill, side hill, or downhill) position. Status (live/dead) of individual trees was recorded 2 years postfire with the exception of a subset of plots where individual trees were inventoried between 3 and 5 years postfire. In those instances, a tree was considered to be alive 2 years postfire if it was recorded as being alive during the 3- to 5-year postfire inventory. This type of imputation was not performed for dead trees. Trees recorded as dead included those that were top-killed (i.e., main bole killed) and resprouting as a result of the fire.

Statistical Analyses

Validation—In FOFEM v. 6.3 (Lutes 2016), BehavePlus v. 3.0 (Andrews and others 2005), and, for all but eight species (*Quercus montana*, *Quercus alba*, *Quercus coccinea*, *Quercus rubra*, *Quercus velutina*, *Acer rubrum*, *Nyssa sylvatica*, and *Carya*, in the Southern variant (SN) of FFE-FVS (Rebain 2010), the probability of postfire mortality for trees >1 inch DBH is modeled using the equation presented by Ryan and Amman (1994) (equation 1), which has the form:

$$P(m) = \frac{1}{1+e^{(-1.941+6.316(1-e^{-BT})-0.000535CS^2)}} \quad (1)$$

where:

P(m) =probability of individual tree mortality (0-1)

BT = bark thickness (in)

CS= crown volume scorched (%).

Crown volume scorched is a function of crown length scorched which is estimated using measurements of scorch height or predicted flame length combined with measurements of total tree height and crown ratio (Van Wagner 1973). For eastern species other than *Pinus palustris*, BT is estimated as a linear relationship between a species-specific multiplier (Lutes 2016) and DBH.

In FFE-FVS (SN), the probability of mortality following fire of *Quercus alba*, *Quercus montana*, *Quercus coccinea*, *Quercus rubra*, *Quercus velutina*, *Nyssa sylvatica*, *Carya* species, and *Acer rubrum* is modeled using equation 2:

$$P(m) = \frac{1}{1+e^{(\beta_0+\beta_1 DBH+\beta_2 SBC)}} \quad (2)$$

where:

P(m) =probability of individual tree mortality (0-1)

DBH =diameter at breast height (cm)

SBC= maximum point of bole blackening (m)

β_0 - β_2 are species-specific model coefficients presented by Regelbrugge and Smith (1994).

In FFE-FVS (SN), postfire mortality of *Quercus alba* is predicted using the equation specific to *Quercus montana*, and mortality of *Quercus coccinea*, *Quercus rubra*, and *Quercus velutina* is modeled using the general *Erythrobalanus* equation (Regelbrugge and Smith 1994).

Using the independent NPS dataset described previously, we used the batch processing option in FOFEM v. 6.3 to calculate the probability of mortality as predicted by equation 1 for 28 species (table 1). Required input variables in the mortality module of FOFEM v. 6.3 include species, DBH, maximum scorch height, total tree height, and crown ratio. Maximum scorch height was entered as the maximum of CHAR and SCOR. For deciduous broadleaved species, using the maximum of SCOR or CHAR may underestimate the effects of scorch, as SCOR was only obtained when postfire inventories occurred during leaf-on. Because total tree height and crown ratio were not measured during data collection efforts, we used the SN, version 1860, to impute these variables (Keyser 2008). This adds a potential source of error in the validation effort. However, total height and canopy base height, two variables required to calculate crown ratio, are rarely collected in upland hardwood forests as part of normal ecological inventories. In addition, we used our independent dataset to predict the probability of mortality of *Quercus montana*, *Quercus alba*, *Quercus coccinea*, *Quercus rubra*, *Quercus velutina*, *Carya* species, *Acer rubrum*, and *Nyssa sylvatica* using equation 2 and model coefficients from Regelbrugge and Smith (1994).

Accuracy of equations 1 and 2 was assessed using classification tables (Hood and others 2007) and receiver operating characteristic (ROC) curve analysis (Saveland and Neuenschwander 1990). The ROC curve is a plot of the true positive rate (i.e., trees observed dead and predicted dead) versus the false positive rate across a range (0 to 1) of cutoff points (Hosmer and Lemeshow 2000). Models with ROC values ≥0.70 are considered to have an acceptable discrimination between live and dead trees, ROC values ≥0.80 have excellent discrimination, and ROC values ≥0.90 are considered to have outstanding discrimination (Hosmer and Lemeshow 2000). In the classification tables, trees whose predicted probability of mortality was above three specified cut-off values (0.50, 0.70, 0.90) were classified as dead while trees whose predicted probability of mortality was below the cutoff value were classified as live. Values in the classification tables reflect sensitivity

Table 1—Individual tree attributes of species used in the validation and/or development of postfire mortality models

Species	Number of live trees	Number of dead trees	DBH	CHAR	SCOR
			inches[a]	*feet*[a]	*feet*[a]
Acer rubrum	497	145	5.9 ± 3.6 (1.0, 27.6)	1.0 ± 1.6 (0.0, 11.5)	3.8 ± 11.0 (0.0, 98.4)
Acer saccharum	52	4	5.7 ± 4.0 (1.2, 25.1)	0.7 ± 1.3 (0.0, 5.4)	4.0 ± 8.1 (0.0, 29.5)
Carya species	524	49	8.8 ± 3.6 (1.0, 21.1)	1.1 ± 1.6 (0.0, 13.1)	2.1 ± 7.5 (0.0, 65.6)
Cornus florida	100	40	3.0 ± 2.1 (1.0, 9.4)	0.7 ± 0.9 (0.0, 6.6)	5.2 ± 9.1 (0.0, 36.1)
Fraxinus species	49	7	6.6 ± 4.5 (1.0, 20.3)	1.5 ± 2.6 (0.0, 11.5)	2.5 ± 6.8 (0.0, 29.5)
Juniperus virginiana	303	17	8.3 ± 3.2 (1.5, 18.0)	0.7 ± 2.1 (0.0, 16.4)	0.7 ± 3.6 (0.0, 32.8)
Liquidambar styraciflua	110	13	5.8 ± 4.0 (1.0, 17.3)	1.2 ± 2.8 (0.0, 22.3)	3.1 ± 9.1 (0.0, 65.6)
Liriodendron tulipifera	34	4	10.6 ± 6.9 (1.0, 34.3)	2.0 ± 2.6 (0.0, 9.8)	0.6 ± 4.0 (0.0, 24.6)
Nyssa sylvatica	234	105	5.2 ± 4.3 (1.0, 26.3)	2.4 ± 2.7 (0.0, 17.4)	2.5 ± 8.0 (0.0, 65.6)
Ostrya virginiana	31	4	3.0 ± 1.7 (1.0, 8.5)	0.6 ± 1.1 (0.0, 4.9)	1.3 ± 3.4 (0.0, 13.1)
Oxydendrum arboreum	308	55	5.3 ± 3.1 (1.0, 15.7)	1.9 ± 3.4 (0.0, 23.0)	7.5 ± 15.8 (0.0, 82.0)
Pinus echinata	524	40	11.1 ± 3.8 (1.1, 23.7)	7.4 ± 8.7 (0.0, 65.6)	10.7 ± 21.0 (0.0, 98.4)
Pinus rigida	220	43	11.3 ± 4.3 (1.3, 24.1)	4.0 ± 4.2 (0.0, 26.2)	2.7 ± 7.9 (0.0, 45.9)
Pinus strobus	174	43	8.7 ± 4.5 (1.0, 27.0)	1.6 ± 2.1 (0.0, 14.8)	5.4 ± 11.0 (0.0, 59.0)
Pinus taeda	63	13	11.2 ± 4.2 (2.0, 21.2)	6.7 ± 6.6 (0.0, 29.5)	9.8 ± 17.5 (0.0, 59.0)
Pinus virginiana	350	194	8.5 ± 3.5 (1.0, 21.0)	2.8 ± 3.5 (0.0, 23.0)	4.5 ± 11.6 (0.0, 65.6)
Quercus alba	593	43	11.3 ± 5.3 (1.0, 33.2)	1.6 ± 2.6 (0.0, 21.3)	2.5 ± 8.5 (0.0, 65.6)
Quercus coccinea	490	123	12.4 ± 5.0 (1.0, 32.4)	2.2 ± 2.6 (0.0, 32.8)	7.5 ± 19.5 (0.0, 98.4)
Quercus falcata	130	22	9.7 ± 5.7 (1.0, 30.2)	1.8 ± 3.9 (0.0, 36.1)	5.3 ± 11.7 (0.0, 49.2)
Quercus marilandica	119	71	7.5 ± 2.9 (1.1, 17.8)	2.0 ± 2.9 (0.0, 15.7)	7.0 ± 13.3 (0.0, 55.8)
Quercus muehlenbergii	48	2	7.8 ± 3.6 (1.6, 18.8)	0.4 ± 0.9 (0.0, 4.3)	0.0 ± 0.0 (0.0, 0.0)
Quercus montana	821	72	11.0 ± 5.1 (1.1, 38.2)	2.0 ± 3.1 (0.0, 23.0)	5.6 ± 15.2 (0.0, 82.0)
Quercus rubra	94	11	10.2 ± 4.0 (1.1, 20.9)	1.4 ± 1.7 (0.0, 6.6)	0.2 ± 1.8 (0.0, 13.1)
Quercus stellata	375	17	10.1 ± 4.1 (1.3, 28.5)	1.3 ± 2.2 (0.0, 19.7)	1.2 ± 6.5 (0.0, 65.6)
Quercus velutina	383	80	11.1 ± 5.6 (1.1, 30.0)	2.1 ± 3.0 (0.0, 39.4)	3.5 ± 11.0 (0.0, 82.0)
Sassafras albidum	31	43	2.2 ± 1.7 (1.0, 10.0)	2.0 ± 2.1 (0.0, 9.5)	1.8 ± 5.6 (0.0, 31.2)
Tsuga canadensis	35	10	6.9 ± 2.4 (1.7, 13.7)	1.1 ± 1.7 (0.0, 7.2)	10.4 ± 11.0 (0.0, 39.4)
Ulmus species	49	7	4.3 ± 2.6 (1.1, 10.0)	0.8 ± 1.5 (0.0, 5.6)	0.9 ± 4.3 (0.0, 29.5)

DBH=diameter at 4.5 feet above groundline; CHAR=maximum height of bole char; SCOR=maximum height of crown scorch.
[a] Values represent the mean ± standard deviation (minimum, maximum).

(i.e., the proportion of dead trees correctly predicted to die within 2 years postfire) and associated false negative rate (FNR) and specificity (i.e., the proportion of live trees correctly predicted to live within 2 years postfire) and associated false positive rate (FPR). Sensitivity is referred as the true positive rate while specificity is often referred to as the true negative rate. The FPR, which is defined as the proportion of live trees that were incorrectly classified as dead is calculated as 1-specificity. The FNR, which is the proportion of dead trees that were incorrectly classified as live, is calculated as 1-sensitivity. A high FPR indicates the model overpredicted mortality while a high FNR indicates the model underpredited mortality.

Postfire mortality model development—We utilized the aforementioned dataset to develop new models that predict the probability of mortality following prescribed fire. Mortality data are categorical with a binary outcome (live or dead). Consequently, we used generalized linear mixed effects modeling to predict the probability of mortality 2 years post-fire using equation 3:

$$P(m) = \frac{1}{1+e^{(-(\beta_0+\beta_1 X_1+\beta_2 X_2+\beta_n X_n))}} \quad (3)$$

where:

P(m) is the probability of morality 2 years following prescribed burning

β_0 through β_n are the regression coefficients

X_1 though X_n are explanatory variables.

For both deciduous broadleaved and conifer species, tree-level explanatory variables tested were DBH and CHAR. These variables were utilized for a variety of reasons: (1) these variables are easily incorporated into the FOFEM and FFE-FVS modeling frameworks (e.g., CHAR is estimated to be 70 percent of modeled flame length (Rebain 2010); (2) DBH is a morphological variable easily obtained during pre- and postfire inventories; (3) relationships between DBH and bark thickness, a variable that may better predict postfire mortality, are unavailable for many upland tree species; and (4) CHAR is a fire effects variable readily obtained during postfire inventories. Models were fitted using maximum likelihood methods and the adaptive Gaussian Quadrature method (METHOD=QUAD) in PROC GLIMMIX (SAS Institute 2015). Plot was included as random effects to account for the fact that trees were nested within a plot. Species-specific models were developed when the number of events (i.e., dead trees) was ≥ to $5p$, where p is the number of explanatory variables (Vittinghoff and McCulloch 2007). Adequate sample size, therefore, equated to a minimum of 10 dead trees (table 1). Model goodness-of-fit was assessed using ROC curve analysis (Saveland and Neuenschwander 1990) using the conditional (i.e., incorporating random effects) predicted values. As a caveat, postfire mortality dynamics for *Pinus virginiana* in this study could have been influenced by a *Dendroctonus frontalis* outbreak that occurred within the Great Smoky Mountains National Park in eastern Tennessee during the late 1990s.

RESULTS

Validation

At the 0.50 cutoff value, which is most commonly used to signal mortality (Lutes 2016), total accuracy of equation 1 varied from 11 percent for *Ostrya virginiana* and *Acer saccharum* to 71 percent for *Quercus montana* and *Pinus taeda* (table 2). At the 0.50 cutoff, model sensitivity was varied between 21 and 100 percent. Although sensitivity values for the majority of species were above 50 percent, specificity, which provides information on how well equation 1 predicted survival, was comparatively low. The false positive rate (i.e., 1-specificity) of equation 1 at the 0.50 cutoff level was relatively high, indicating equation 1 vastly overpredicted mortality for the species examined. Total accuracy of equation 1 increased as the cutoff value increased for all species examined other than *Sassafras albidum*. The increase in total accuracy achieved by using a higher cutoff value corresponded to decrease in model sensitivity and an increase in model specificity. Of the 28 species validated, only 10 were found to have acceptable levels of discrimination (i.e., ROC values ≥0.70) (table 2).

The ROC values associated with equation 2, which was developed using data specific to the species modeled, indicated acceptable to excellent discrimination (table 3). Total accuracy at the 0.50, 0.70, and 0.90 cutoff values exceeded 70 percent for all eight species examined. Across the cutoff values, survival was more accurately predicted than mortality. At the standard 0.50 cutoff value, sensitivity was greatest for *Quercus velutina* (69 percent) while specificity was greatest for *Nyssa sylvatica* (99 percent). The ROC values indicated that relative to equation 1, equation 2 performed similarly for *Acer rubrum* (ROC 0.807 versus 0.817), but outperformed equation 1 for *Carya* species, *Nyssa sylvatica*, *Quercus alba*, *Quercus coccinea*, *Quercus montana*, *Quercus rubra*, and *Quercus velutina*. At the standard 0.50 cutoff value, the FPR, or overprediction of mortality, of species

Table 2—Classification table representing the validation of the Ryan and Amman (1994) postfire mortality model (equation 1) as implemented in the FOFEM v. 6.3 (Lutes 2016) at 0.50, 0.70, and 0.90 cutoff values

Species	ROC	Total accuracy	Sensitivity (FNR)	Specificity (FPR)	Total accuracy	Sensitivity (FNR)	Specificity (FPR)	Total accuracy	Sensitivity (FNR)	Specificity (FNR)
		0.50 cutoff value			*0.70 cutoff value*			*0.90 cutoff value*		
Acer rubrum[a]	0.817	26	100 (0)	5 (95)	56	92 (8)	46 (54)	76	6 (94)	97 (3)
Acer saccharum	0.800	11	100 (0)	4 (96)	52	100 (0)	48 (52)	93	14 (86)	100 (0)
Carya species[a]	0.726	49	67 (37)	47 (53)	91	51 (49)	95 (5)	92	14 (86)	99 (1)
Cornus florida	0.568	29	100 (0)	1 (99)	42	88 (12)	24 (76)	63	13 (87)	83 (17)
Fraxinus species	0.832	38	100 (0)	29 (71)	73	100 (0)	69 (31)	89	14 (86)	100 (0)
Juniperus virginiana	0.851	34	88 (12)	31 (69)	87	76 (24)	87 (13)	94	6 (94)	99 (1)
Liquidambar styraciflua	0.663	24	92 (8)	15 (85)	57	77 (23)	55 (45)	87	8 (92)	96 (4)
Liriodendron tulipifera	0.901	61	100 (0)	56 (44)	87	75 (25)	88 (12)	87	0 (100)	97 (3)
Nyssa sylvatica[a]	0.796	42	100 (0)	17 (73)	68	92 (8)	56 (44)	67	2 (98)	97 (3)
Ostrya virginiana[a]	0.577	11	100 (0)	0 (100)	17	75 (25)	10 (90)	89	0 (100)	100 (0)
Oxydendrum arboreum	0.651	17	98 (2)	3 (97)	53	67 (33)	50 (50)	80	24 (76)	90 (10)
Pinus echinata	0.613	52	65 (35)	51 (49)	85	30 (60)	90 (10)	87	30 (70)	92 (8)
Pinus rigida	0.528	63	21 (79)	72 (28)	81	2 (98)	96 (4)	83	0 (100)	100 (0)
Pinus strobus	0.721	56	72 (28)	52 (48)	78	42 (59)	87 (13)	85	42 (58)	96 (4)
Pinus taeda	0.569	71	38 (62)	78 (22)	78	0 (100)	94 (6)	79	0 (100)	95 (5)
Pinus virginiana	0.630	48	92 (8)	24 (76)	62	17 (83)	87 (13)	64	6 (94)	96 (4)
Quercus alba[a]	0.695	60	81 (19)	58 (42)	90	16 (84)	96 (4)	92	5 (95)	98 (2)
Quercus coccinea[a]	0.652	68	58 (42)	71 (29)	76	25 (75)	89 (11)	77	15 (85)	93 (7)
Quercus falcata	0.530	52	55 (45)	52 (48)	74	36 (64)	81 (19)	85	14 (96)	97 (3)
Quercus marilandica	0.731	51	99 (1)	23 (77)	66	44 (56)	80 (20)	66	28 (72)	89 (11)
Quercus muehlenbergii	0.609	32	50 (50)	31 (69)	78	0 (100)	81 (19)	96	0 (100)	100 (100)
Quercus montana[a]	0.666	71	54 (46)	73 (27)	86	28 (72)	91 (9)	88	3 (97)	95 (5)
Quercus rubra[a]	0.654	63	64 (36)	63 (37)	91	36 (64)	98 (2)	90	0 (100)	100 (100)
Quercus stellata	0.574	56	53 (47)	56 (44)	93	12 (88)	96 (4)	94	0 (100)	99 (1)
Quercus velutina[a]	0.724	68	60 (40)	70 (30)	82	35 (65)	92 (8)	79	10 (90)	94 (6)
Sassafras albidum	0.619	58	100 (0)	0 (100)	62	98 (2)	13 (87)	49	14 (86)	97 (3)
Tsuga canadensis	0.657	31	100 (0)	11 (89)	69	40 (60)	77 (23)	80	30 (70)	94 (6)
Ulmus species	0.545	14	100 (0)	2 (98)	32	86 (14)	24 (76)	88	0 (100)	100 (0)

ROC=area under the Receiver Operating Characteristics curve; Total accuracy=the percentage of trees correctly classified as either live or dead; Sensitivity (FNR)=the percentage of trees observed dead that were correctly predicted to die within 2 years postfire (false negative rate (1-sensitivity)); Specificity (FPR)=the percentage of trees observed live that were correctly predicted to survive 2 years postfire [false positive rate (1-specificity)].

[a] Indicates the probability of mortality calculated in FFE-FVS (SN) is achieved via equation 2.

modeled using equation 2 was substantially lower than equation 1.

Postfire Mortality Models

For *Liquidambar styraciflua*, *Pinus rigida*, *Pinus taeda*, *Quercus rubra*, and *Tsuga canadensis,* neither DBH nor CHAR were significant predictors of postfire mortality. For all species other than *Quercus falcata* and *Quercus stellata*, we observed a significant and negative relationship between the probability of mortality and DBH (table 4). This negative relationship implies the probability of mortality within 2 years following prescribed fire decreases as DBH increases. For *Juniperus virginiana* and *Pinus echinata*, CHAR had no significant relationship with the probability of mortality. For all other species, the probability of mortality was significantly and positively related to CHAR (table 4). With the exception of *Quercus alba*, which had an acceptable level of discrimination (ROC=0.795), ROC values indicated the newly developed postfire models had excellent (ROC >0.8) to outstanding (ROC >0.9) discrimination.

DISCUSSION

The goals of this study were to (1) validate existing postfire mortality models used by nationally supported fire behavior and fire effects models; (2) develop new species-specific postfire mortality models for prominent upland forest tree species in the Southeastern United States using individual tree and fire effects data commonly collected during postfire inventory procedures; and (3) compare accuracy of the equations produced by Ryan and Amman (1994) and Regelbrugge and Smith (1994) with the newly developed equations.

Validation

The use of postfire mortality models developed for western conifer species (equation 1) inadequately predicted postfire mortality of the eastern tree species examined in this study. Equation 1 overpredicted mortality overall and by as much as 100 percent (using the standard 0.50 cutoff) for some species (e.g., *Ostrya virginiana* and *Sassafras albidum*). Not surprisingly, the postfire mortality equations developed specifically for a subset of the tree species examined in this study (equation 2) more accurately predicted mortality than equation 1. For example, at the standard 0.50 cuttoff value, equation 1 correctly predicted mortality (i.e., sensitivity) of 54 percent of the *Quercus montana* trees in our dataset compared to 64 percent using equation 2. For the majority of species examined, equation 1 predicted mortality more accurately than survival (i.e., specificity), while equation 2 predicted survival more accurately than mortality. Our results support the notion that widespread application of models built with data outside the geographic range of application, let alone across functional groups (i.e., conifer versus deciduous broadleaved species), results in poor model performance (Wang and others 2007). Model performance errors of the magnitudes observed in this study have the potential to misrepresent the ecological effects of prescribed burning on species composition and stand density—two attributes actively managed through prescribed burning programs across upland forests of the Southeastern United States.

Postfire Mortality Models

Stem size (i.e., DBH) and severity of fire effects (i.e., CHAR), singularly or in concert, significantly predicted the probability of individual tree mortality 2 years following prescribed fire for all species other than *Liquidambar styraciflua*, *Pinus rigida*, *Pinus taeda*, *Quercus rubra*, and *Tsuga canadensis*, (i.e., neither DBH or CHAR were significant). For 16 of the 17 species examined, we observed a significant and inverse relationship between the probability of mortality following prescribed burning and DBH. Stem size has been proven to be a significant predictor of postfire mortality of numerous eastern and western tree species (Beverly and Martell 2003, Hood and Bentz 2007, Hood and others 2010). Although significant, the strength of the relationship between the probability of mortality and DBH varied considerably across species, and was likely a reflectance of species-specific relationships between stem size and bark thickness (Harmon 1984). Individuals with larger DBH, and consequently greater bark thickness, experience lower maximum cambial temperatures and an increased time to reach peak temperature, providing greater protection from cambial injury (Hengst and Dawson 1994) and subsequent mortality.

Crown damage is commonly used to predict mortality of western conifer species (Hood and others 2010, Keyser and others 2006). Because the vast majority of prescribed burns in the southeastern upland forests are conducted during the dormant season, estimates of crown/foliage damage are rarely possible to obtain for deciduous broadleaved species. In addition, because maximum scorch height associated with prescribed burns in upland forests of the Southeastern United States is low (<3 feet) (Arthur and others 2015), crown damage is rarely observed following prescribed burning for either conifer or deciduous broadleaved species. Consequently, we fitted postfire mortality models using CHAR in lieu of crown damage or maximum height of crown scorch (SCOR) values. The probability of mortality for all the deciduous broadleaved species and all but two conifer species (*Juniperus virginiana* and *Pinus echinata*) modeled was positively associated with CHAR. Maximum height of bole char, which is an indirect measurement of cambial damage (Wyant and others 1986) and related to flame length (Rebain 2010), is positively correlated with tree mortality (Arthur and others 2015) and has been successfully used to predict mortality of conifer and deciduous broadleaved species, including *Pinus ponderosa* (Regelbrugge and Conard 1993), *Populus tremuloides* (Hély and others 2003), *Quercus kelloggii* (Cocking and others 2012), and various Appalachian hardwood species (Regelbrugge and Smith 1994). When crown damage and bole char height are used in combination to predict postfire mortality, crown damage is usually the stronger of the two predictors (Rigolot 2004). However, in systems where crown damage is negligible or cannot be accurately measured (e.g., as is the case for dormant deciduous broadleaved species), results from previous studies (Cocking and others 2012, Regelbrugge and Smith 1994) coupled with results presented here suggest bole char height adequately predicts postfire tree mortality.

CONCLUSION

The equations developed in this study outperformed the general Ryan and Amman (1994) equations for all species examined, suggesting models used by nationally supported fire effects and behavior models to predict postfire tree mortality should be developed using data specific to a given species or species group obtained from the geographic area of interest. Furthermore, models that use fire effects data to predict mortality should include fire effects data relevant to a given species or species group. Models utilized by fire effects programs, including FOFEM and FFE-FVS, as well as the models developed in this study are rudimentary and utilize the most basic of fire effects (i.e., DBH and crown damage as predicted by flame length or scorch height) to predict postfire mortality. The probability a tree dies following fire is confounded by many factors other than scorch/char height and tree size, including prefire growth rates (van Mantgem and others 2003), fine-root mortality (Swezy and Agee 1991), season of burn (Harrington 1993), postfire insect activity (Menges and Deyrup 2001), tissue necrosis (Bova and Dickinson 2005), and abiotic conditions at the time of burn [e.g., duff moisture (Varner and others 2007)].

The newly developed postfire mortality models presented here used easily obtained tree and fire effects data, and should be considered a step towards the development of short- and long-term fire-related mortality models as related to prescribed burning for eastern tree species. The new equations presented in this study were developed using data from low-severity prescribed fire conducted primarily during the dormant season. Therefore, it is not known how well these equations will perform for trees damaged by higher severity prescribed or wildfire, or following growing season burn events. However, the high levels of model discrimination displayed by equation 2, which was developed using data following wildfire, suggests separate models for predicting postfire mortality following prescribed versus wildfire may not be necessary, but this should be a subject of future investigation. The models we developed forecast mortality 2 years postfire. Evidence from western (Thies and others 2006) and eastern (Yaussy and Waldrop 2008) systems document a delay in mortality that can extend through the fourth year following prescribed fire. Lack of more detailed fire effects and fire behavior data in combination with longer tree mortality data limited our ability to explore more complex relationships among delayed tree mortality and the myriad of fire effects known to influence postfire mortality. To improve upon or expand the use of the models developed in this study, we recommend collecting additional data

Table 3—Classification table representing the validation of the Regelbrugge and Smith (1994) postfire mortality model (equation 2) as implemented in the FFE-FVS (SN) (Rebain 2010) at 0.50, 0.70, and 0.90 cutoff values

Species	ROC	Total accuracy	Sensitivity (FNR)	Specificity (FPR)	Total accuracy	Sensitivity (FNR)	Specificity (FPR)	Total accuracy	Sensitivity (FNR)	Specificity (FPR)
		0.50 cutoff value			*0.70 cutoff value*			*0.90 cutoff value*		
Acer rubrum	0.807	78	48 (52)	42 (58)	76	24 (76)	91 (9)	75	11 (89)	94 (6)
Carya species	0.805	92	53 (47)	95 (5)	91	29 (71)	97 (3)	92	14 (86)	99 (1)
Nyssa sylvatica	0.886	79	34 (66)	99 (1)	75	19 (81)	100 (0)	71	8 (92)	100 (0)
Quercus alba	0.798	92	51 (49)	95 (5)	94	47 (53)	97 (3)	94	21 (79)	99 (1)
Quercus coccinea	0.734	77	54 (46)	83 (17)	80	41 (59)	90 (10)	81	24 (76)	95 (5)
Quercus montana	0.866	92	64 (36)	94 (6)	93	45 (55)	97 (3)	93	23 (77)	99 (1)
Quercus rubra	0.743	77	45 (55)	81 (19)	82	18 (82)	89 (11)	90	18 (82)	98 (2)
Quercus velutina	0.796	75	69 (31)	77 (23)	81	58 (42)	86 (14)	83	35 (65)	92

ROC=area under the Receiver Operating Characteristics curve; Total accuracy=the percentage of trees correctly classified as either live or dead; Sensitivity (FNR)=the percentage of trees observed dead that were correctly predicted to die within 2 years postfire (false negative rate (1-sensitivity)); Specificity (FPR)=the percentage of trees observed live that were correctly predicted to survive 2 years postfire [false positive rate (1-specificity)].

Table 4—Parameter estimates (standard error) associated with species-specific models for predicting 2-year mortality following a single prescribed burn

Species	β_0	β_1	β_2	ROC
Acer rubrum	1.5665 (0.5419)	-0.7910 (0.1082)	0.3600 (0.1180)	0.900
Carya species	-1.7070 (0.7405)	-0.3077 (0.0740)	0.3524 (0.1301)	0.964
Cornus florida	-0.9436 (0.4995)	-0.3741 (0.1459)	1.2042 (0.3519)	0.831
Juniperus virginiana	4.4307 (3.7436)	-1.9250 (0.6086)	NS	0.994
Nyssa sylvatica	2.0139 (0.7099)	-1.4082 (0.2358)	0.4579 (0.1311)	0.974
Oxydendrum arboreum	0.6011 (0.8520)	-0.9661 (0.2258)	0.5513 (0.1200)	0.957
Pinus echinata	-2.2510 (1.0604)	-0.2774 (0.0992)	NS	0.975
Pinus strobus	-3.0327 (1.6098)	-0.2673 (0.1327)	0.7908 (0.2683)	0.983
Pinus virginiana	0.8526 (0.6354)	-0.3855 (0.0598)	0.2359 (0.0556)	0.929
Quercus alba	-1.7759 (0.4147)	-0.1564 (0.0443)	0.2621 (0.0432)	0.795
Quercus coccinea	-1.6085 (0.4826)	-0.0945 (0.0315)	0.2262 (0.0638)	0.917
Quercus falcata	-3.3149 (0.9240)	NS	0.2643 (0.1305)	0.960
Quercus marilandica	0.2854 (0.8636)	-0.2497 (0.1094)	0.4615 (0.1240)	0.906
Quercus montana	-1.6320 (0.5843)	-0.3651 (0.0609)	0.4112 (0.0702)	0.951
Quercus stellata	-4.2562 (0.5525)	NS	0.3635 (0.0895)	0.915
Quercus velutina	0.1500 (0.5486)	-0.3311 (0.0670)	0.3848 (0.0859)	0.916
Sassafras albidum	1.3997 (0.6211)	-2.1525 (0.5236)	2.4615 (0.5756)	0.935

Model coefficients: β_0=intercept; β_1=diameter at breast height (inches) (DBH); β_2=maximum height of stem char (feet) (CHAR); ROC=area under the Receiver Operator Characteristics curve; NS=not significant.

related to (1) longer term postfire mortality and severity of fire effects from the range of forest types and resultant species compositions, (2) edaphoclimatic conditions, and (3) prescribed burning goals and objectives inherent to upland forests of the Southeastern United States, including season of burn.

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