PRESCRIBED SURFACE-FIRE TREE MORTALITY IN SOUTHERN OHIO: EQUATIONS BASED ON THERMOCOUPLE PROBE TEMPERATURES

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ABSTRACT.—In the spring of 2001, experimental prescribed burns were conducted on three 20-ha treatment areas in the Ohio Hills of southern Ohio. Each treatment area contained ten 20- 50-m plots on which every tree >10 cm in diameter at breast height was inventoried before the burns. The plots also were instrumented with thermocouple probes which recorded probe temperature every 2 seconds during the burn. Tree mortality on the plots is described and compared with predictions from a series of physically based equations describing the flames, stem heating, tissue necrosis, and stem death. Equations for bark thickness and crown volume were developed for 13 species to help predict the ability of a tree to survive the heat from a fire. Fire effects are inferred from thermocouple probe temperature regimes and a calibrated probe heat budget. The equations provide a means of linking an important fire effect (stem death) with fire behavior and thermocouple data.

Prescribed fire has been suggested as a method to ensure the sustainability of the upland oak ecosystem of the Central Hardwoods region by controlling thin-barked, competing species such as red maple (Sutherland 1997). Bark serves as insulation, but thinner bark, present on smaller trees or thin-barked species makes a stem more susceptible to mortality from the heat applied to the lower bole by surface fires. Heat from intense flames penetrates the bark and kills the cambium, often resulting in fatal injuries. Research in western conifer forests has shown that cambium damage and crown scorch due to surface fires are closely associated with tree mortality (Reinhardt and Ryan 1989). It is assumed that bark thickness is the mechanism by which species differ in resistance to heat from surface fires.

Smoldering duff can heat root systems to the point of necrosis and subsequent mortality (Sackett and Haase 1992). Few models relate fire behavior to tree mortality in eastern hardwood forests. Absent a severe spring drought in this region, the duff does not dry sufficiently to allow burning or smoldering. After placing probes 1 cm below the soil surface, Iverson and Hutchinson (2001) recorded a maximum temperature of 27.6°C. In this paper we investigated only mortality due to aboveground heat from surface fires.

Bark thickness equations exist for tree species in the Central Hardwoods region, but most predict diameter inside bark given diameter outside bark at heights at or above 1.37 m (Hengst and Dawson 1994; Hilt and others 1983). We developed models for bark thickness below 1.37 m and crown diameter for 13 hardwood species. Stepwise logistic regression was used to estimate tree mortality based on measured or calculated tree variables, fire variables (derived from thermocouple readings), and combinations of the two.

Methods

The data used here were collected for two separate studies: the Ohio Hills site of the Fire and Fire Surrogate (FFS) study and the Ohio Hills National Fire Plan project (OHNFP). As part of the OHNFP, we used a digital micrometer to measure the thickness of three bark wedges chiseled from trees at 0, 15, 50, and 137 cm. Minimum and maximum crown width were measured by laser range finder for each tree to develop a linear equation for estimating average crown diameter based on DBH for each of the 13 species (Table 1).

A two-stage estimation process was used to develop an empirical model of lower bole bark thickness based on DBH since the measurements for an individual tree are not independent. In the first stage a nonlinear model of bark thickness by height for each tree was developed. In the second stage, DBH was used to predict the coefficients of the stage-one model for each species. Combining these models results in an equation for predicting species-specific bark thickness based on DBH for any height near the base of a tree.

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The FFS study encompasses 13 sites throughout the United States. At each site the same core variables are collected to evaluate the mechanical removal of biomass to simulate the effects of fire in ecosystems that developed with low-intensity, high-frequency fire regimes (Weatherspoon 1999). At each site, four treatments (control, mechanical removal, prescribed fire, and a combination of prescribed fire and mechanical removal) were replicated 3 times. The replications at the Ohio Hills site are in southern Ohio on the Raccoon Ecological Management Area (REMA), and the Tar Hollow (TAR) and Zaleski (ZAL) State Forests. Each 20-ha treatment area within each replication contains ten 20- by 50-m plots on which vegetation is sampled. Pretreatment measurements were taken in the summer of 2000 and prescribed burning was conducted in late March and early April of 2001. Post-treatment data were collected in 2001 and 2002. Because we are concerned with the effect of heat from prescribed fires on the mortality of overstory trees, we have included only the data from the areas that were burned but not thinned to reduce the confounding of mortality associated with factors such as logging damage and compaction. Only plots and trees with the full range of variables were used.

On the vegetation plots, we recorded the species of each tree more than 10 cm DBH as well as DBH, mortal status, height to the base of the live crown (hbc), total height, and three crown variables before treatment (Table 2). Two years after treatment, we recorded mortal status, and height of bark char. Crown assessment measurements were adapted from the North American Maple Project and consisted of:

> Fine twig dieback, i.e., branch mortality that begins at the terminal portion of a limb and progresses inward:
>
> 0 = no or trace dieback present
> 1 = less than 10 percent
> 2 = 10 to 25 percent
> 3 = 26 to 50 percent
> 4 = 51 to 75 percent
> 5 = 76 to 100 percent
>
> Defoliation — an estimate of the amount of foliage removed by chewing insects or foliar pathogens. The same scale for crown dieback was used.
>
> Vigor — an impression of overall crown health. Vigor differs from dieback and defoliation in that it estimates what is not present. For example, a recent windstorm may have caused crown breakage and removed a portion of a crown:
>
> 1 = 10 percent or less branch or twig mortality, foliage discoloration, crown area missing, or abnormality present
> 2 = 11 to 25 percent of the crown missing/injured
> 3 = 26 to 50 percent of the crown missing/injured
> 4 = 51 to 75 percent of the crown missing/injured
> 5 = 76 to 100 percent of the crown missing/injured

During the prescribed fires a data logger located at the center of each plot recorded the temperature (every 2 seconds) of a rigid stainless steel rod with a thermocouple encased at the tip (Fig. 1). From these temperature readings we constructed the maximum temperature attained by the probe during the fire as well as the length of time the temperature remained above 30°C, a level somewhat above ambient air temperature. Few temperature profiles were recorded during the fire at TAR due to user error in deploying the data recorders. Almost all data recorders worked at the REMA and ZAL replications. Only data from plots which recorded temperatures were used in this analysis (Table 3).

With the equations for bark thickness and crown diameter, we were able to assign a bark thickness at 15 cm (representative of the area affected by surface fires) and crown dimensions to each tree from the FFS study based on pretreatment species and DBH measurements. The crowns of the trees were represented by ellipsoids based on crown length and width.

Table 1.—Mean and standard deviation (in parentheses) for datasets used to develop models for bark thickness and crown diameter (OHNFP)

	Species												
Variable	Red maple *Acer rubrum*	Sugar maple *Acer saccharum*	Hickories *Carya spp.*	Dogwood *Cornus florida*	Beech *Fagus grandifolia*	Yellow-poplar *Liriodendron tulipifera*	Blackgum *Nyssa sylvatica*	Sourwood *Oxydendrum arboreum*	White oak *Quercus alba*	Scarlet oak *Quercus coccinea*	Chestnut oak *Quercus prinus*	Red oak *Quercus rubra*	Sassafras *Sassafras albidum*
Trees (no.)	33	16	22	15	32	33	28	35	27	11	36	11	13
DBH (cm)	14.703 (9.155)	9.975 (5.626)	10.391 (5.307)	6.980 (2.761)	10.316 (6.616)	11.745 (7.939)	8.054 (4.629)	12.400 (6.243)	13.137 (4.146)	15.064 (5.929)	13.247 (9.250)	10.491 (5.708)	10.708 (3.259)
Crown diameter (m)	5.996 (2.283)	4.425 (2.154)	3.202 (1.213)	3.591 (0.967)	5.714 (1.632)	3.638 (1.043)	3.731 (1.286)	4.033 (1.345)	3.763 (1.429)	3.626 (1.419)	4.059 (1.969)	3.380 (1.519)	3.163 (0.888)
Bark thickness (cm)	4.794 (2.597)	4.476 (2.339)	9.987 (4.621)	4.126 (1.528)	2.219 (1.488)	8.761 (4.957)	6.250 (2.907)	9.148 (4.491)	7.691 (2.653)	10.820 (3.914)	13.079 (6.283)	9.274 (4.598)	8.650 (3.388)

Table 2.—Mean and standard deviation (in parentheses) for datasets used to develop models for logistic model (FFS)

	Species												
Variable	Red maple	Sugar maple	Hickories	Dogwood	Beech	Yellow-poplar	Blackgum	Sourwood	White oak	Scarlet oak	Chestnut oak	Red oak	Sassafras
Trees (no.)	230	47	32	5	5	35	31	46	98	28	146	26	4
Dead (no.)	21	1	3	2	0	1	0	7	7	2	9	3	0
Dead (%)	9.130	2.128	9.375	40.000	0.000	2.857	0.000	15.217	7.143	7.143	6.164	11.538	0.000
DBH (cm)	17.111 (7.166)	15.945 (8.401)	27.053 (16.161)	10.700 (0.469)	12.300 (2.826)	25.643 (14.804)	15.152 (7.278)	14.435 (3.961)	37.357 (15.484)	40.564 (11.336)	37.233 (12.953)	43.123 (20.085)	30.650 (1.448)
Vigor (index)	1.235 (0.542)	1.170 (0.380)	1.125 (0.336)	2.400 (1.673)	1.000 (0.000)	1.086 (0.373)	1.097 (0.301)	1.543 (0.836)	1.459 (0.887)	1.357 (0.678)	1.411 (0.802)	1.115 (0.326)	1.250 (0.500)
Dieback (index)	1.174 (0.463)	1.085 (0.282)	1.094 (0.390)	2.600 (1.517)	0.800 (0.447)	1.057 (0.236)	1.065 (0.359)	1.804 (0.806)	1.429 (0.873)	1.643 (0.678)	1.281 (0.702)	1.231 (0.430)	1.250 (0.500)
Defoliation (index)	1.030 (0.315)	1.064 (0.247)	1.125 (0.421)	1.800 (1.789)	1.200 (0.447)	0.971 (0.169)	0.935 (0.250)	1.065 (0.533)	1.010 (0.550)	1.036 (0.508)	1.144 (0.599)	1.038 (0.196)	1.000 (0.000)
Char height (m)	0.508 (0.610)	0.334 (0.366)	0.523 (0.852)	0.480 (0.602)	0.220 (0.192)	0.900 (0.992)	0.629 (0.931)	1.296 (1.148)	0.664 (1.011)	0.829 (0.692)	0.516 (0.710)	0.919 (0.701)	0.900 (1.003)
Height to base of live crown (m)	7.081 (2.428)	5.825 (2.236)	9.728 (3.908)	4.756 (1.518)	2.378 (0.818)	9.460 (3.637)	5.881 (3.113)	6.071 (2.037)	11.193 (2.529)	11.923 (1.426)	11.452 (2.828)	12.629 (2.329)	8.155 (4.078)
Crown length (m)	5.068 (2.316)	7.045 (2.485)	4.192 (1.917)	2.683 (0.950)	8.720 (4.014)	5.174 (2.657)	4.032 (1.945)	2.757 (1.236)	5.068 (1.990)	4.617 (1.456)	4.369 (1.822)	4.468 (1.374)	7.927 (2.240)
Bark thickness (cm) at 15 cm	0.587 (0.158)	0.793 (0.291)	2.353 (1.082)	0.466 (0.006)	0.292 (0.047)	1.626 (0.616)	0.989 (0.270)	1.047 (0.169)	1.530 (0.392)	2.020 (0.292)	2.474 (0.466)	2.358 (0.658)	3.053 (0.165)
Crown volume (m^3)[a]	128.772 (113.586)	209.632 (331.624)	89.833 (100.992)	30.351 (10.495)	190.280 (124.492)	86.758 (106.475)	72.692 (67.025)	29.491 (20.707)	352.604 (348.022)	187.294 (103.272)	186.588 (142.009)	348.623 (318.276)	94.044 (30.257)
Crown scorch (%)[a]	0.624 (5.266)	1.305 (4.599)	0.000 (0.000)	13.545 (30.287)	22.853 (29.066)	3.416 (17.001)	6.672 (22.378)	6.605 (23.175)	0.000 (0.000)	0.000 (0.000)	0.773 (8.305)	0.000 (0.000)	0.000 (0.000)
Depth-to-thickness ratio[a]	0.781 (0.232)	0.496 (0.164)	0.209 (0.078)	0.816 (0.363)	1.520 (0.232)	0.293 (0.134)	0.422 (0.089)	0.415 (0.107)	0.302 (0.096)	0.226 (0.048)	0.176 (0.072)	0.217 (0.079)	0.124 (0.035)
Depth minus thickness[a]	-0.156 (0.186)	-0.430 (0.308)	-1.934 (1.066)	-0.087 (0.169)	0.143 (0.054)	-1.215 (0.654)	-0.589 (0.256)	-0.622 (0.195)	-1.099 (0.391)	-1.574 (0.307)	-20.61 (0.495)	-1.890 (0.669)	-2.671 (0.115)

[a] Values calculated from modeled data, all other variables were measured.

Table 3. —Mean and standard deviation (SD) of FFS plot-level data used in logistic regression (plots: n=22)

Maximum temperature		Duration		Byram's fire intensity[a]		Height of crown scorch[a]		Depth of necrosis[a]	
Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
°C		seconds		kw/m		m		cm	
162.445	(51.269)	729.818	(380.849)	140.547	(53.605)	3.940	(1.006)	0.431	(0.091)

[a] Values calculated from modeled data; all other variables were measured.

While Byram (1959) demonstrated the relationship between a subjective estimate of flame length and fireline intensity, a method of Bova and Dickinson (2003), was used to estimate Byram's fireline intensity from the maximum temperatures recorded by the temperature probes located in the center of each vegetation plot. The interaction between flames, winds, and tree boles cause uneven heating on different sides of larger trees, leading to an underestimation of mortality for those trees. As such, this method may be expected to work better for small trees that do not interrupt the fluid flow sufficiently to cause significant uneven heating. Bova and Dickinson (2003) have developed an equation that relates the depth of cellular necrosis in living trees to Byram's intensity. If this estimated depth was greater than bark thickness, cambial tissue likely would be killed, and stem death was predicted.

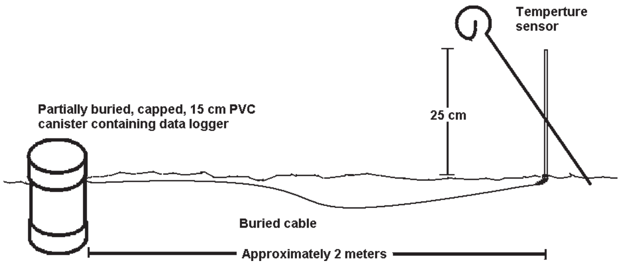

Figure 1.—Schematic of field installation of temperature probe.

Height of crown scorch was calculated with Bova and Dickinson's (2003) estimate of intensity and with the equations of Van Wagner (1973). An estimate of the percentage of the crown that was scorched by the fire was calculated for each tree in the plots based on scorch height, hbc, crown length, and crown volume.

A forward stepwise logistic regression was used to evaluate the ability of the variables, actual and constructed, to predict overstory tree mortality on the vegetation plots of the Ohio Hills site of the FFS study. Variables included measurements, calculations, and combinations of crown health, DBH, bark thickness, depth of necrosis, crown scorch, intensity, and char height (Tables 2-3).

Results

Statistics for the bark- and crown-dimension dataset and the FFS dataset are presented in Tables 1 and 2, respectively. Coefficients for the linear regression of crown diameter by DBH are listed in Table 4 for the 13 species in this study.

Graphs of several of the height-thickness relationships suggested fitting an exponential function for the first stage of the bark thickness equation:

$$BT = a + b * \exp(c * \text{height})$$

where:

BT = Bark thickness estimated by regression
a, b, and c = Regression coefficients.

The intercept term was not significant and was dropped so that the final model fit to each tree was:

$$BT = a * \exp(b * \text{height}).$$

Table 4.—Regression coefficients for crown diameter and bark thickness models

Species	Crown diameter[a]		Bark thickness[b]		
	b_0	b_1	b	c	d
Red maple	2.885	0.212	-0.003	0.899	0.680
Sugar maple	1.662	0.308	-0.002	0.984	0.770
Hickories	1.753	0.141	0.002	1.810	0.778
Dogwood	1.594	0.286	0.000	2.447	0.271
Beech	3.632	0.213	-0.005	0.519	0.719
Yellow-poplar	2.440	0.102	-0.004	2.044	0.668
Blackgum	1.765	0.248	-0.001	1.851	0.632
Sourwood	1.979	0.166	-0.001	1.073	0.617
White oak	0.331	0.261	-0.002	1.843	0.600
Scarlet oak	0.700	0.193	-0.004	3.351	0.504
Chestnut oak	1.665	0.181	-0.004	4.391	0.498
Red oak	1.002	0.227	-0.007	3.291	0.557
Sassafras	2.336	0.079	-0.002	0.630	1.143

[a] Crown diameter = $b_0 + b_1 * DBH$.

[b] Bark Thickness = c * DBH^d * exp(b * height).

The second stage used DBH to predict the coefficients of the stage one model for each species. Graphical observation suggested:

$$\hat{a} = c + d * DBH^e$$

where:

$\hat{a}$ = First-stage coefficient to be estimated by second-stage regression
c, d, and e = Regression coefficients.

Again the intercept was not significant and the final model fit to each species was:

$$\hat{a} = c * DBH^d.$$

DBH was not correlated to the "b" parameter; therefore, the mean within each species was used. Combining these models results in an equation to predict species-specific bark thickness based on DBH for any lower bole height:

$$BT = c * DBH^d * \exp(b * height).$$

Coefficients for these models also are listed in Table 4. The models differentiate bark thickness by species; beech (Table 1 includes common and scientific names) and red maple having the thinnest bark while hickory and chestnut oak have the thickest (Fig. 2). Sassafras appears to develop thick bark slowly but continually.

The final logistic regression model contains the variables for which the coefficients differed from zero at the 0.05 level. These include dieback, duration, depth of necrosis to bark thickness ratio (depth-to-thickness), and char height, none of which was correlated (r > 0.500). The model is of the form:

$$P_m = 1-1/(1+\exp(-8.6622+1.4091*dibak+0.00215*duration+3.1740*dtratio+0.4649*char))$$

where:

P_m = Probability of mortality
dibak = Fine twig dieback
duration = Length of time the temperature of the probe remained above 30°C (seconds)
dtratio = Depth-to-thickness ratio
char = Char height.

These variables allow the model to attain a rank correlation of 0.730 (Somer's D statistic).

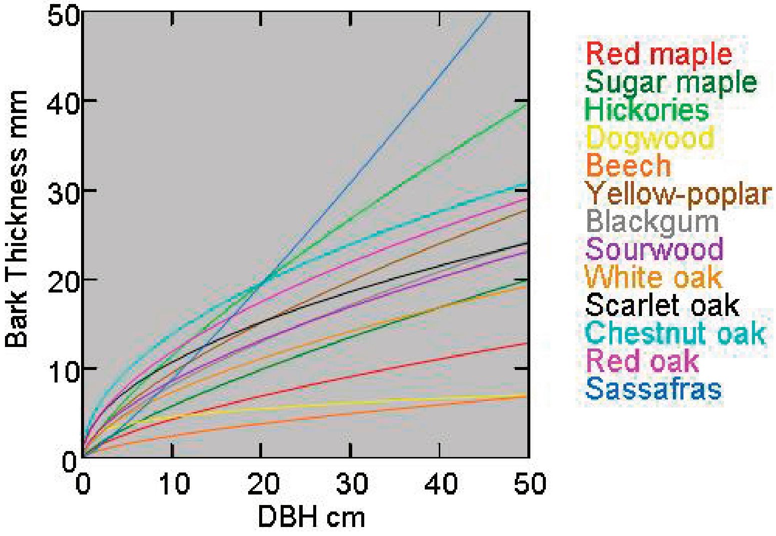

Figure 2.—Bark thickness at 15-cm height by DBH for 13 hardwood species.

Discussion

The DBH ranges of many of the species in the FFS dataset extend well beyond those of the dataset used to create the crown diameter and bark thickness equations (Tables 1-2). However, the models are well behaved within the range of tree sizes expected to be affected by fire, and are assumed to be applicable to the entire range of FFS data.

Forward stepwise logistic regression allows the user to see which variables or sets of variables add significantly to the prediction of mortality. All variables are assessed singly for their contribution to reducing the variability of the model. As new variables are entered, the remaining variables are reassessed based on their contribution to the new, larger, model. Dieback reduced the variation slightly more than vigor and was introduced to the model first. Once dieback was included, vigor no longer contributed much to the reduction of variance. Thus, although vigor was more highly correlated to mortality than all other variables except dieback, it was not included in the final model.

The five beech trees in the FFS dataset had the greatest predicted depth-to-thickness ratio and the largest predicted percent crown scorch (Table 2), yet none of these trees died. Bark char was lowest for beech, indicating that fire intensity at each bole may have been low compared to plot-level predictions. Beech had the shortest mean hbc. The relatively large crown with low limbs gives the trees high shade tolerance and may provide resistance to fire by protecting the boles from fuel build-up. If the lower limbs are killed in a fire, these trees still may have sufficient crown to maintain adequate photosynthesis—but also a higher probability of mortality in subsequent fires.

If these five beeches are removed from the dataset, percent crown scorch and depth of necrosis minus bark thickness (depth minus thickness) enter the model. Depth-to-thickness ratio and depth minus thickness are highly correlated and only depth-to-thickness ratio should be included in the model. This formulation of the data and model improved the predictive capability only slightly (Somer's D = 0.740).

Logistic regression typically is used to model tree mortality (Stringer and others 1989; Regelbrugge and Smith 1994; Reinhardt and Ryan 1989; Ryan and others 1988) Another method for modeling the effects of surface fire on tree mortality is stepwise discriminate analysis. This method results in identical independent variable selection and similar predictive capabilities.

Conclusion

Measured and estimated variables were used to construct a logistic model to predict mortality of trees two years after a prescribed fire in southeastern Ohio. The most significant indication of tree mortality following fire is the health of the tree prior to the fire. If the tree is under stress, as indicated by crown dieback or vigor assessments, it may be more susceptible to mortality with the added stress of fire effects. Equations were developed to estimate species and DBH specific bark thickness and crown structure. These estimates, along with estimates of heat transmission processes, added to the predictive ability of a logistic model. However, effective strategies may have evolved in tree species with thin bark, such as beech, to limit the build-up of fuels from around their boles enabling them to survive surface fires.

Estimates of fire intensity and duration from a single point are associated with the likelihood of mortality of trees up to 25 meters from the point, but can be refined, somewhat, with rough surrogates for intensity (char height) measured at each tree. More accurate models will be possible with microsite estimates of intensity possibly based on fuel loading and climatic conditions.

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