

INVESTIGATING THE RELATIONSHIP BETWEEN BOLE SCORCH HEIGHT AND FIRE INTENSITY VARIABLES IN THE RIDGE AND VALLEY PHYSIOGRAPHIC PROVINCE, WEST VIRGINIA

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Abstract.—Prescribed fires are carried out on the George Washington National Forest (GWNF) in West Virginia to promote long-term resource and social values, including tree regeneration, improving wildlife habitat and aesthetics, and maintenance of low woody fuel loading. Prescribed fire programs have increased on the GWNF over the past 20 years. Although prescribed fire is widely used on the GWNF, methods and techniques for monitoring fire behavior are still in the early stages of development. As part of a larger study to assess the effects of prescribed fire on invasive species in eastern West Virginia, we used simple linear correlation and regression analysis to investigate the relationships between plot-level 3-year post-fire bole scorch height parameters, fire temperature as estimated by thermocouple probes, litter consumption, and sapling mortality to better understand and predict fire effects in mixed-oak and oak-pine forests. We collected information on these parameters as they were observed on 36 research plots in an area where a prescribed fire had been applied in the Ridge and Valley physiographic province of eastern West Virginia. The prescribed burn totaled 313.6 ha and was conducted in March 2004. Neither overstory nor sapling bole scorch height variables were significantly related to thermocouple temperature measurements recorded at five locations on a southwest-facing slope ($\alpha = 0.05$). The sum of the sapling scorch heights was significantly related to litter consumption, but accounted for only 11 percent of the variation. However, all bole scorch height variables were significantly related to sapling mortality one growing season after the fire. This result further illustrates the usefulness of scorch height as an estimator of relative fire intensity, and provides a useful prediction model for xeric mixed-oak and oak-pine fire managers.

INTRODUCTION

Prescribed fire is primarily used on West Virginia's George Washington National Forest (GWNF) to manage areas unsuitable for timber production. These sites are often characterized by infertile soils, steep/rocky slopes, noncommercial/low-value species mixtures, or pine-oak stands in general (USDA Forest Service 1993). The fires are applied to promote long-term resource and social values such as maintenance of low woody fuel loading, aesthetics, tree regeneration, and increased abundance of such understory plants are valuable for wildlife forage as blueberries (*Vaccinium* spp.), huckleberry (*Gaylussacia baccata*), scrub oak (*Quercus ilicifolia*), and various grasses. Since the mid- to late-1980s, the extent of these fires has increased quite dramatically (Fig. 1). During the 1980s, GWNF managers treated, on average, 37.2 hectares/year, compared to 877.2 hectares/year in the 1990s and 2,097.0 hectares/year this decade. Those averages equate to an astounding 2,240 percent from the 1980s to the 1990s, and a 140 percent increase from the 1990s to the 2000s.

Several studies have examined fire behavior in a number of various regions. However, fire behavior-related studies in the Appalachian region are limited (Franklin and others 1997, Clinton and others 1998, Vose

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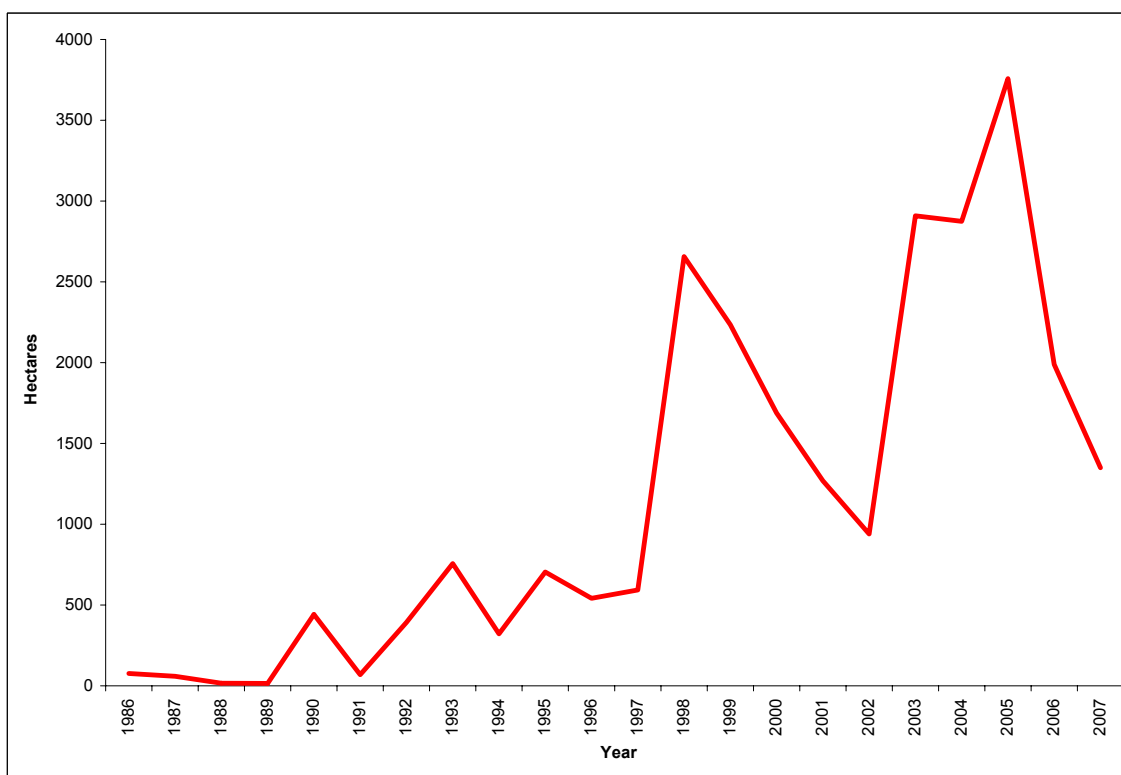


Figure 1—Area treated with prescribed fire by year on the George Washington National Forest.

and others 1999, Iverson and others 2004). Although prescribed fire is widely used on the GWNF, methods and techniques for monitoring fire behavior are still in the early stages of development.

Bole scorch height, otherwise known as stem-bark char or height of bole blackening, has been proven to be a significant predictor of post-fire mortality in various forest types (Loomis 1973, Regelbrugge and Conrad 1993, Regelbrugge and Smith 1994, Wyant and others 1986). It has also been proven to be highly correlated with areal percent canopy scorch and top-kill of individual trees (Regelbrugge and Smith 1994). Although bole scorch height underestimates flame length in prescribed burns (Cain 1984), these findings indicate that it can be used to estimate relative fire intensity at the stand level.

As part of a larger study to assess the effects of prescribed fire on invasive species in eastern West Virginia, we investigated the relationship between plot-level 3-year post-fire bole scorch height parameters (independent variables) and other fire intensity variables to better understand and predict fire effects in mixed-oak and oak-pine forests. A better understanding of the role of fire in determining the structure and composition of xeric mixed-oak and oak-pine forests of the Ridge and Valley physiographic province will enhance management efforts to sustain these forests.

We focus on the relationships between measured variables and the usefulness of these parameters for: predicting changes in stand structure. Three relationships/predictions will be evaluated, including (1) litter consumption as a function of scorch height; (2) thermocouple estimated fire temperature as a function of scorch height; and (3) sapling mortality as a function of scorch height. The intent of this analysis is to evaluate whether these quick, simple, and inexpensive field measurements can help characterize prescribed fire behavior and its short-term effects on forest structure and composition. We expect increasing litter consumption, thermocouple temperature, and sapling mortality with increasing bole scorch height.

METHODS

Study Site

Our research was conducted at Dunkle Knob, located on the North River Ranger District (formerly the Dry River Ranger District) of the GWNE, Pendleton County, WV (38° 37' N, 79° 14' W). Our study area included 313.6 ha and is composed of xeric mixed-oak and oak-pine communities. The area is within the Ridge and Valley province and is in the rain-shadow of the Allegheny Mountains, which causes a climate that is much drier than the rest of the state (Core 1966). The area is characterized by an average annual precipitation of 82 cm, an average annual temperature of 10.9 °C, and a growing season of approximately 144 days (Estepp 1992). Forests of the region can be characterized as being part of the former oak-chestnut cover type (Braun 1950).

The topography is highly dissected with slopes ranging from 6 to 70 percent. Elevation ranges from 573 to 848 m. The predominant soil type is of the Berks-Weikert association. Soils are loamy-skeletal, mixed, Dystrochrepts formed from acidic shale, siltstone, or sandstone bedrock. The soils are droughty and infertile and often contain numerous rock outcroppings (Estepp 1992).

The Dunkle Knob area was purchased by the USDA Forest Service in 1923. There have been no documented fires in the Dunkle Knob area from its purchase date up to the time of the prescribed fire (Marsh 2005). Dunkle Knob was treated with a prescribed fire on March 29, 2004. Air temperatures ranged from 11 to 21 °C and relative humidity ranged from 29 to 76 percent. Winds were primarily from the northwest and southeast at a speed of 2-10 km/H. The interior of the mountain was ignited in a northeast-southwest pattern from top to bottom by a helicopter dropping delayed aerial ignition devices. The perimeter, established using existing roads and limited new fire line construction, was ignited by personnel on the ground using drip torches (Marsh 2005).

Pre-fire (2003) total basal area for the overstory (trees ≥ 12.7 cm diameter at breast height [d.b.h.]) averaged 20.8 m²/ha, and increased to 23.0 m²/ha by 2007. Chestnut oak (*Quercus prinus*), table mountain pine (*Pinus pungens*), and Virginia pine (*P. virginiana*) made up 66.5 percent of the overstory basal area in 2007.

Field Methods

Thirty-six circular 0.05-ha overstory plots were randomly established at the Dunkle Knob study site during the summer of 2003 (pre-fire). Eighteen plots were randomly established on northeast (315-235°) and southwest (236-314°)-facing slopes. Within each aspect class, nine plots were established above and below 748 m elevation. To aid in future relocation, sample points were located with a global positioning system (GPS) and a piece of steel rebar was driven into the ground at plot center. In addition, plot boundaries were flagged.

Each plot was inventoried in the summers of 2003 (pre-fire), 2004 (one growing season post-fire) and 2007, three full growing seasons after the fire. All overstory trees (d.b.h. > 12.7 cm), both living and dead, were tallied. Each tree was identified to species (although a small number of dead trees could not be positively identified), and crown class was recorded. Stem diameter was measured to the nearest 0.1 cm using a diameter tape. During the 2007 inventory, bole scorch height, defined as height of the highest point of bole blackening on the uphill face of the tree (Regelbrugge and Smith 1994), was measured to the nearest 15 cm using a height pole. The sapling layer (all trees 2.54 cm $\leq$ d.b.h. $\leq$ 12.6 cm) was sampled using a circular 0.01-ha plot located at the center of each overstory plot (n = 36). All saplings were identified to species and d.b.h. Bole scorch height on saplings was also recorded as described above.

Also within each overstory plot, 1 m² circular plots were established at 12.06 m from the overstory plot center in each of the four cardinal directions (n = 144). These were primarily for understory vegetation measurements; however, litter layer (Oi) depth was measured to the nearest 0.1 cm at the west end of each plot using a ruler in 2003 (pre-fire) and 2004 (3-4 months post-fire).

On five south-facing overstory plots, 9.14 m² square sampling plots were established. On these plots, the prescribed fire itself was monitored using a network of thermocouple probes. These sample points were selected due to logistical considerations and the expectation that the prescribed fire would be the most intense on southerly aspects (Marsh 2005). At the corners and at the center of these square plots, 25 cm thermocouple probes were installed and HOBO® data loggers (Onset Computer Corporation, Bourne, MA) were buried just below the surface in a manner similar to that of Iverson and others (2004) and set to record thermocouple temperature at 4-second intervals the day of the prescribed fire. All data loggers were collected immediately following the treatment. It is well known that Type K thermocouple probes cannot record flame or air temperature around the probe during a prescribed fire because of the lag time of the probes and the relatively short duration of the most intense heating (Iverson and others 2004). However, it was our desire to use a small sample of thermocouple probe temperature data to characterize fire behavior on what we believed would be the most intense area of the fire, and to assess its usefulness for predicting fire effects.

Analytical Methods

Pre- and post-fire litter depth (LD) measurements were averaged for each overstory plot (n = 4), and litter consumption was quantified by the average percentage change in these values (n= 36). Litter consumption was calculated using the equation:

$$\text{Litter Consumption} = \left(\frac{(LD_{post} - LD_{pre})}{LD_{pre}} \right) * 100$$

Scatter plots were used to graphically examine all relationships for linearity, as well as any potential non-linear relationships. Following graphical examination, simple linear correlation and regression analysis were performed to examine the relationship between litter consumption (dependent) and both overstory and sapling bole scorch height measures (mean and sum) (independent) for all plots. The sum of hardwood tree heights is commonly used as a measure of hardwood competition in young southern pine plantations. Similarly, we tested the sum of the scorch heights as an independent variable that combines the number of stems scorched and degree of charring to determine its usefulness as a surrogate for fire behavior.

The analysis was also performed separately for mostly scorched plots. In this study, mostly scorched plots are defined as plots in which ≥50 percent of the overstory trees were scorched. This separate analysis was performed in hopes of reducing within-plot scorch height variability. This method reduced this variability considerably in a pilot study of plot level bole scorch height against temperature-sensitive paint used to estimate fire temperature from another prescribed fire in a mixed-oak stand in the Ridge and Valley province².

Linear correlation and regression were also used to examine the relationships between recorded thermocouple temperature (dependent) and bole scorch height parameters.

²Data on file with the USDA Forest Service, Northern Research Station, Parsons, WV.

Table 1.—Average scorch height parameters(cm) by stratum

Stratum	Mean	Sum
Overstory	56.01	1450.41
Sapling	38.37	286.08

Both means were significantly different between strata at $\alpha = 0.05$.

Table 2.—Relationships between bole scorch height variables (cm) and litter consumption (%) for all plots

Stratum	Variable	r	R ²	P
Overstory	Mean	0.20	0.04	0.253
	Sum	0.14	0.02	0.407
Sapling	Mean	0.29	0.09	0.128
	Sum	0.33	0.11	0.049*

*Indicates significance at $\alpha = 0.05$

To better understand how post-fire stand structure attributes were influenced by surrogates of fire intensity, a third correlation/regression analysis was performed to observe how the change in the number of understory living saplings (percent mortality) varied with plot-level bole scorch height variables.

All statistical analyses were performed using SAS 9.1 software (SAS Institute, Cary, NC, 2003), with significance determined at an $\alpha = 0.05$. Effects of independent variables were assessed using the General Linear Model procedure. Mean comparisons were evaluated with paired t-tests. The DFFITS procedure was used to examine plot data and identify influential observations (outliers). The SAS DFFITS procedure identified one plot as a statistical outlier. Therefore this plot was removed from the analyses. Interestingly, this was the only plot in the study area in which the overstory was dominated by pitch pine (*Pinus pungens*) (>50 percent of the overstory basal area). Both average and sum of the scorch heights on this plot were much greater than on others.

RESULTS AND DISCUSSION

Litter Consumption

Immediately following the prescribed fire, litter depth differed significantly from pre-fire conditions. The fire, on average, resulted in a 49.5 percent decrease in litter depth (2.14 cm in 2003 compared to 1.08 cm in 2004). Average 3-year post-fire bole scorch height variables were significantly different between the overstory and understory strata based on paired t-tests. Loucks and others (2004) found that mean scorch heights increased with larger diameter classes in an Appalachian hardwood forest in Kentucky. Similarly, our study showed means that were significantly higher for the overstory stratum (Table 1). These scorch height differences suggest that researchers or managers interested in measuring scorch height should also stratify their sample by these forest layers.

Neither of the overstory stratum independent variables (mean and sum of the scorch heights) could effectively predict litter consumption (Table 2). The sum of the sapling scorch heights, however, proved to be a significant litter consumption predictor. Unfortunately, the model can account for only 11 percent

Table 3.—Relationships between bole scorch height variables (cm) and litter consumption (%) for plots with ≥50 percent of the trees scorched (n = 18)

Stratum	Variable	r	R ²	P
Overstory	Mean	0.22	0.05	0.393
	Sum	0.10	0.01	0.634
Sapling	Mean	0.35	0.12	0.168
	Sum	0.45	0.20	0.060

Table 4.—Relationships between bole scorch height variables (cm) and fire temperature (°C) for 5 plots fitted with thermocouples

Stratum	Variable	r	R ²	P
Overstory	Mean	0.62	0.39	0.264
	Sum	0.70	0.50	0.184
Sapling	Mean	0.04	0.002	0.940
	Sum	0.14	0.02	0.823

of the variation in litter consumption. More intricate fuel measurements (e.g., fuel transects and moisture content) may show stronger relationships to the measured variables than simple percentage change in litter depth. Mass changes in the litter layer may alter ecosystem functions, but can be time-consuming to measure. Developing efficient methods for estimating such changes would be helpful to forest managers. The fire effects on the litter layer were similar to the work of Brown and others (1991) and Elliot and others (2002).

Contrary to our expectations, the results were similar when the analysis was restricted to plots in which greater than 50 percent of the trees were scorched (Table 3). Even though we found a positive linear correlation, there was little evidence that any measure of scorch height was a useful predictor of litter consumption, due to the large amount of unexplained variation in the model. The most promising explanatory variable in this restricted analysis was the sum of the sapling scorch heights ($P = 0.060$). We suspect that the weak correlation between these variables is due to the litter layer itself. That is, given the thin pre-fire litter layer (2.14 cm on average) plots experiencing even the modest intensity would likely lose nearly their entire litter layer. Future efforts to develop easy-to-measure predictor variables to estimate litter consumption should narrow the ecological amplitude of the explanatory variables to potentially improve model performance.

Thermocouple Temperature

Although we found a general positive relationship between scorch height and thermocouple temperature, there was little evidence of a useful predictive relationship (Table 4). When compared to litter consumption predictions, R^2 values were, in general, higher for overstory scorch height-based thermocouple temperature predictions. This value is larger, however, probably because only a small number of points could be used to examine the relationships between scorch height and thermocouple temperature.

It should be emphasized that our thermocouple temperatures used in the analysis were the average of five thermocouple probes on each plot. Due to the limitation of such instrumentation, averaging probe

Table 5.—Sapling mortality (%) models and associated statistics

Model	r	R ²	SEE	P
%Mort.= 4.03 + 0.39(mean overstory scorch height [cm])	0.79	0.63	4.37	<0.001*
%Mort.= 9.75 + 0.01(sum of overstory scorch heights [cm])	0.69	0.47	4.89	<0.001*
%Mort.=10.96 + 0.39(mean sapling scorch height [cm])	0.42	0.18	7.28	0.010*
%Mort.= 16.41 + 0.03(sum of sapling scorch heights [cm])	0.44	0.19	5.87	0.008*

*Indicates significance at $\alpha = 0.05$

temperature may mask significant spatial variability among fire intensity throughout the sample area, ultimately weakening the relationship. Despite our results, we speculate that useful predictive relationships between thermocouple probe temperatures and fire effects could be developed if more spatially limited procedures were utilized. Employing more intensive sampling would likely limit bias and produce more indicative and statistically significant results as well. However, the time-consuming nature of using thermocouple probes combined with their potentially limited spatial extrapolations may ultimately restrict their usefulness by managers.

Sapling Mortality

Total pre-fire number of living saplings averaged 1000 trees per hectare (TPH), compared to 725 TPH in 2004. These values were significantly different ($P < 0.001$). Chestnut oak, pignut hickory (*Carya glabra*), Virginia pine, and striped maple (*Acer pensylvanicum*) made up 53.7 percent of the number of saplings in 2007.

There was ample evidence of a relationship between scorch height and sapling mortality induced by the prescribed fire. All overstory and sapling layer scorch height variables were significant predictors of sapling mortality (Table 5). We plan further analysis to assess species-specific predictive relationships. Average overstory bole scorch height provided the strongest relationship and accounted for 63 percent of the variation in sapling mortality (Fig. 2). By contrast, Regelbrugge and Smith (1994) found that the average scorch height accounted for 96 percent of the variation in the percentage of the number of fire-killed trees. However, their study was conducted in the aftermath of a 1900 ha wildfire which exhibited greater amplitude in scorch height and fire severity than the Dunkle Knob prescribed fire we monitored. They also chose stands with both low and high fire severity to provide a wide range of fire intensity and subsequent effects. Our results further illustrate the usefulness of this relationship even when conditions are much more homogenous.

When the sapling mortality analysis was restricted to mostly scorched plots, relationships/models were not nearly as sound. Therefore, these results were not reported.

CONCLUSIONS

Our results indicate that, at the plot level, the measured 3-year post-fire overstory and sapling bole scorch height variables (mean and sum) are not significantly correlated to litter consumption or thermocouple temperature. The results do, however, indicate that sapling mortality (one growing season post-fire) is a function of the tested bole scorch height parameters, with the strongest independent variable being average overstory scorch height. This finding further illustrates the usefulness of scorch height as an estimator of relative fire intensity and fire effects, and will allow for an examination of how relative fire intensity relates to changes in exotic-invasive plant populations (the larger study).

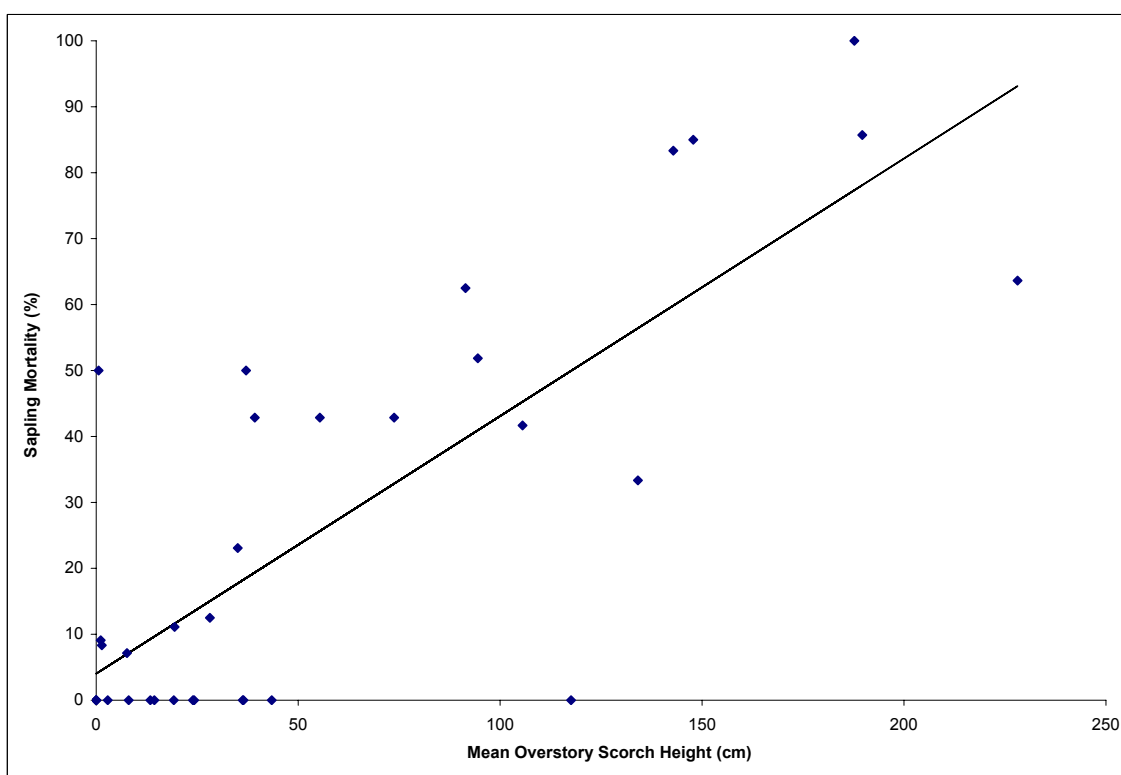


Figure 2.—The relationship between mean overstory scorch height (cm) and sapling mortality (%).

The relationship between average scorch height and sapling mortality also has the potential to be very useful for xeric mixed-oak and oak-pine fire managers. The mean overstory scorch height model indicates that 50 percent mortality can be expected at an average overstory scorch height of just over 1 m. An average overstory scorch height just less than 2 m would result in about 75 percent sapling mortality. An average overstory scorch height of about 2.5 m would likely result in 95 percent mortality. This model can be used to make a quick and inexpensive assessment of fire-induced mortality in areas where pre- and post-fire saplings were not sampled. Managers could also use the information to adjust ignition patterns to alter the potential sapling mortality in similar xeric mixed-oak and oak-pine prescribed fires.

However, the model does have its limitations. It has not been tested against independent data, and should therefore be considered preliminary. Nonetheless, we do feel that the model will provide a sensible estimate of plot-level sapling mortality (1 year post-fire). Use of the model should be limited to xeric mixed-oak and oak-pine forests of the Ridge and Valley physiographic province. Also, due to the statistical outlier and its removal, model predictions should not be applied when pitch pine makes up a high percentage (>50 percent) of the basal area in the area being burned.

Further analysis of existing information about both dependent and independent variables is planned to better understand the relationships examined. For example, measures of scorch height models of mortality may be different for disparate species such as red maple (*Acer rubrum*) and chestnut oak. Also, because topography is related to scorch height (Loomis 1973), the effect of slope percent, aspect, elevation, slope position, landform shape, etc. should be examined. Loucks and others (2004) found higher scorch heights in more xeric locations. Logistic or multiple regression models may provide improved predictions by incorporating these and other influential variables.

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