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ABSTRACT OF THESIS

THE EFFECTS OF LANDSCAPE SCALE PRESCRIBED FIRE ON FUEL LOADING AND TREE HEALTH IN AN APPALACHIAN HARDWOOD FOREST, KENTUCKY

Increasing use of prescribed fire in Appalachian hardwood forests has generated questions concerning the effects on fuel loads and health of overstory trees. Although prescribed burning may enhance oak regeneration and thin stands while reducing fuel loads, prescribed fire may damage potential timber trees. Objectives of this research were to: 1) characterize fuel loads and document fuel reductions, and 2) examine the factors affecting bark scorch heights. A repeated measures split-plot design was used to detect differences in fuels by treatment (burned or unburned), sampling time (preburn, postburn, and 10-months postburn), and landscape position (mesic, intermediate, or xeric). Large woody fuel mass (>7.6 cm diameter) and the Oea layer of the forest floor differ by landscape position, with more Oea on xeric positions and more large woody fuels on mesic positions. Litter (Oi) and small 1-hour woody fuels were reduced ($p<0.05$) postburn, but did not differ from preburn fuel loads 10-months postburn. Using regression modeling, nine variables and four interaction terms including species, DBH, and landscape position, were found to influence maximum bark scorch height on trees >2 cm DBH. This information will be important to forest managers as they plan ecosystem prescribed fires in the region.

KEYWORDS: prescribed burning, bark scorch, fuel load, fire intensity, landscape position

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THE EFFECTS OF LANDSCAPE SCALE PRESCRIBED FIRE
ON FUEL LOADING AND TREE HEALTH
IN AN APPALACHIAN HARDWOOD FOREST, KENTUCKY

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CHAPTER ONE

Introduction

Paleontological data indicate that ground fires due to anthropogenic ignitions have occurred in central Appalachian forests for the past 3000 thousand years and possibly longer (Delcourt et al., 1998). Fires continued in the region after European settlement, often resulting in intense slash fires in recently logged areas (Pyne 1982). In response to growing concern about fire in the forest, the United States Forest Service started a policy of fire suppression in the 1940s which successfully decreased the extent of ground fires in eastern forests. Before fire suppression, the disturbance from repeated fires may have prevented fire sensitive species from succeeding onto the drier upland sites, allowing oak species to dominate (Reich et al., 1990). Fire suppression is believed to have contributed to an increased abundance of fire sensitive species, such as red maple (*Acer rubrum* L.) and American beech (*Fagus grandifolia* Ehrh.) on upland forest sites (Lorimer, 1985; Reich et al., 1990). Although the loss of American chestnut (*Castanea dentata* (Marsh.) Borkh; (McCormick and Platt, 1980) and forest harvesting (Lorimer, 1992) may also have contributed to the increase in fire sensitive species. Prescribed fire is increasingly being used by forest managers in Appalachian and central hardwood regions as a forest management tool, and in the 1990s managers in the Daniel Boone National Forest, Kentucky, began using prescribed fire in an effort to remove fire sensitive species from upland sites, increase biodiversity, and improve the resilience and stability of ecosystems (U.S. Forest Service, 2003).

Although prescribed burning may reduce the amount of competition from faster growing, fire-sensitive species and thereby improve regeneration of oaks, studies to date have yielded inconclusive evidence (Wendel and Smith, 1986; Van Lear and Waldrop, 1989; Kuddes-Fischer and Arthur, 2002; Gilbert et al., 2003). Low intensity ground fires can alter forest stand structure by killing small diameter or thin barked trees, but simultaneously cause an increase in sprouting of fire-sensitive and oak species alike (Blankenship and Arthur, 1999; Elliott et al., 1999). The reduction of midstory stem density temporarily allows more light to penetrate through to the forest floor, but a rapid flush of sprouts causes canopy closure to return to pre-fire levels within four years (Chiang, 2002).

Additionally, prescribed fire is being promoted as a tool for reducing fuel loads and wildfire risk in Appalachian and central hardwood forests, since prescribed burns have reduced fuels and the severity of subsequent fires in wide-ranging ecosystems (Pyne et al., 1996;

Fernandes and Botelho, 2003). Although previous studies have found prescribed fires in mature Appalachian and central hardwood forests reduce litter (Oi) and small woody fuels (Clinton et al., 1998; Riccardi and McCarthy, 2002; Kolaks et al., 2004), few studies have reported reductions in large woody fuels (Hubbard et al., 2004), which comprise a large portion of the fuel bed. Further, there is little information on the recovery of fuel bed in subsequent months or years (Thor and Nichols, 1973; Hartman, 2004), and no previous research has been published on fuel loads in the mountainous regions of eastern Kentucky.

Fear of damaging potential timber trees and reducing their merchantable value is a serious concern for many forest managers (Brose and Van Lear, 1999) and may limit the desirability of using prescribed fire to reduce fuel loads and competing vegetation in hardwood stands. Bark scorch heights have been used in Missouri for estimating fire-caused mortality and injury on oak and hickory species (Loomis, 1973). However, the correlation between bark scorch height and tree mortality and wounding for other hardwood trees species has not been reported. Additionally, bark scorch heights have been used as a relative measure of fireline intensity in pine stands (Cain, 1984) and there may be potential for using scorch heights as a measure of intensity in hardwood stands.

The objectives of this study were to document (1) the fuel loading and change in fuel loads after a prescribed fire, and (2) the differences in maximum bark scorch height on tree boles after prescribed fire. Obtaining baseline fuel data will allow for the long term study of the effects of fire on fuel components and total loading, while the examination of bark scorch heights may lead to better predictions of tree damage after fire and to discovery of a tree species or tree size that can be correlated with fire intensity in the future.

CHAPTER TWO

Characterization and reduction of fuel after a single prescribed fire in an Appalachian hardwood forest, Kentucky

1. Introduction

In light of paleontological data indicating that ground fires have occurred in Appalachian forests for the past 3000 years (Delcourt et al., 1998), and suggestions that prescribed fire may be a tool for reducing competition from fast growing, fire sensitive species and thereby improve regeneration of oaks (Van Lear and Watt, 1993), a burgeoning use of prescribed fire is occurring in the central Appalachian region. Prescribed fire is also a tool used worldwide for reducing fuel loads and wildfire risk (Fernandes and Botelho, 2003), and has been shown to reduce fuel loads in southern and western pine ecosystems (Pyne et al., 1996) and after forest harvesting in eastern forests (Swift et al., 1993). However, there is little evidence to suggest that prescribed fire significantly reduces fuel loadings, or the ability of the forest floor to carry fire repeatedly, in mature hardwood forests (Thor and Nichols, 1973; White, 1983; Huddle and Pallardy, 1996). Typically, only immediate reductions in woody fuel and forest floor mass after a single prescribed fire have been reported for central and Appalachian hardwood forests (Clinton et al., 1998; Riccardi and McCarthy, 2002; Kolaks et al., 2004). The long term effects of fire on fuel accumulation, even during the next fire season, are not well understood. No previous studies have examined the fuel loads in the mountainous regions of eastern Kentucky. Nonetheless, many forest managers consider fuel reduction an additional benefit of ecosystem management fires in central and Appalachian hardwood forests.

In deciduous hardwoods, the forest floor litter, or Oi layer, is a primary fuel capable of carrying fire across the landscape, and the litter layer receives annual additions during autumn leaf fall, potentially rendering deciduous forests flammable in consecutive years. Dead, down woody fuels are also a potentially important fuel influencing fire spread and duration (Pyne et al., 1996). Little or no reduction in humus (Oa) has been reported from low intensity prescribed fire (Vose and Swank, 1993; Blankenship and Arthur, 1999; Hubbard et al., 2004), and humus has little influence on fire spread due to the compactness and normally high moisture content of humus in Appalachian forests. However, during extended periods without rainfall, humus may be consumed in slow moving fires due to the longer heat exposure, and humus and woody fuels may continue to burn long after the main fire front has passed (Pyne et al., 1996).

Forest floor and woody fuel mass varies spatially within central and Appalachian hardwood forests (Blow, 1955; Muller and Yan, 1991) and is attributed to topography, tip-up mounds, soil type, decomposing organisms, site history including insect defoliation, and weather events such as ice storms (Wallace and Freedman, 1986). Rapid decomposition rates in Appalachian hardwood forests (Mudrick et al., 1994; Idol et al., 2001) may lead to relatively low total fuel loads despite the lack of fire in some forests for decades. Fire intensity and burn severity are both affected by forest floor and dead, down woody fuel loads, with fire intensity referring to the rate of heat release during fire, while burn severity refers to the physical and chemical changes to fuels, soil, and vegetation as a result of fire.

This study was designed to describe the fuel load in a southern Appalachian hardwood forest in eastern Kentucky, and to evaluate the effect of landscape position and prescribed fire on fuel load. I hypothesized that litter (Oi) accumulation would vary topographically, with litter fuel loads being higher on lower slope positions due to the redistribution of leaf litter downslope after leaf fall (Orndorff and Lang, 1981; Boerner and Kooser, 1989). Secondly, I hypothesized that fuel reduction from prescribed fire would occur primarily in the litter layer and small woody fuels, and that fuel reductions would vary by landscape position, with xeric plots having hotter fires and therefore a greater reduction in fuels. Finally, I hypothesized that fuel loads after autumn leaf fall, 10 months after the prescribed fires, would be similar to preburn fuel loads.

2. Methods

2.1 Site Description

Three study sites were chosen within the Morehead Ranger District of the Daniel Boone National Forest (DBNF) in eastern Kentucky, Buck Creek (Menifee and Bath Counties), Chestnut Cliffs (Menifee County), and Wolfpen (Bath County). The study sites are between 194 and 293 ha, and are located within an 18 km^2 area. The mean annual temperature is 12.2 °C with mean daily maximum and minimum temperatures in January of 7 °C and -5 °C, and in July, 30 °C and 16.5°C (Hill, 1976). Mean annual precipitation is 109 cm spread evenly throughout the year, with approximately 38 cm of snowfall each winter (Hill, 1976). Elevation ranges from 260 to 360 m (850 to 1180 ft), and encompasses slopes of varying aspect in each study area. The topography consists of steep slopes and undulating topography which results in site moisture conditions varying from submesic to xeric. Soils are also variable in depth and texture due to the steep unglaciated topography and are classified as Typic Hapludults, Typic Hapludalfs, Ultic Hapludalfs, and Typic Dystrochrepts (Avers, 1974). Sites chosen are not known to have had fires of any kind on them during the last 30 years (Michael Colgan, U.S. Forest Service, Morehead, Ky., pers. com.).

2.2 Experimental Design

Each study site was subdivided into three treatments for use in a long term fire study of the effects of prescribed fire on oak regeneration: one treated with 'frequent' prescribed fires, one treated with 'infrequent' prescribed fires, and a fire-excluded treatment. The treatment areas were 55 to 117 hectares, and contained 8 to 12 plots that were systematically located from a grid overlaid on a topographic map, for a total of 93 plots. The plots were 10 by 40 meters, and oriented parallel to the topographic contour. Plots were categorized into landscape positions (sub-xeric, intermediate, and sub-mesic) (Table 1) based on hill-shading, aspect, slope position, and species composition, resulting in a split-plot design. For simplicity, landscape positions will from hereon be referred to as xeric, intermediate, and mesic.

The first prescribed fires in the frequent and infrequent treatment areas occurred in the spring of 2003. For this study the frequent and infrequent treatment sites were combined into one treatment unit, "burned," because only data from one year of fire is available. The combination of two treatment units into one resulted in an unbalanced design with approximately twice as many plots in the burned treatments as the fire-excluded treatments.

2.3 Fire prescription and temperature measurements

USDA Forest Service personnel of the DBNF conducted the prescribed fires in March and April of 2003 using drip torches and helicopter ignition. The Chestnut Cliff site was burned on two consecutive days, March 24 and 25, with the southern section (Chestnut Cliffs south) burned first. The Buck Creek burn treatment was ignited on April 14, 2003, followed by the Wolfpen burn treatment on April 16, 2003. Ambient weather conditions are given in Table 2. Flame heights and rates of spread were highly variable within and between burn treatments due to ignition along lower slope, mid-slope, and ridge positions.

Fire temperature data recorded during prescribed fires and have been used as an empirical estimate of fire intensity (Cole et al., 1992; Franklin et al., 1997; Clinton et al., 1998; Blankenship and Arthur, 1999). Since it was not possible to record flame length and rate of spread on our plots due to the large and topographically variable study sites and personnel safety concerns, fire temperatures were recorded and used as a surrogate for fire intensity during the prescribed fires. Temperatures were measured using six pyrometers per plot, with three located along each of the two fuel transects. Six Tempilaq® fire sensitive paints representing temperature ranges from 79°C to 482°C were painted onto aluminum tags. Painted tags were attached to pin flag stakes at 20 and 40 cm above the forest floor and on the surface within ten days of the burn. Each tag was covered with a small piece of aluminum foil to prevent water damage and smoke discoloration. The melting point of aluminum, at 644°C, extended the temperature range. The pyrometers were collected within four days of the fires. Mean fire temperatures on each plot were calculated by averaging the highest temperature surpassed on each pyrometer. Temperatures were variable due to ignition intensity and four plots had fire on less than 25% of their total area. The first Chestnut Cliffs burn (March 24) had the lowest mean temperatures surpassed, while the Wolfpen burn (April 16th) had the hottest mean temperatures

(Table 2). One plot in Chestnut Cliffs (north) did not have pyrometers in place before the prescribed fires. Less than 10 percent of this plot burned, resulting in an inappropriately high temperature range and mean maximum temperature for the Chestnut Cliffs (north) burn due to the omission of mean temperatures for that plot. Including ambient temperatures for the omitted plot reduces mean maximum temperature by a different amount for each height position with 0 cm reducing to 476° (-57°), 20 cm to 283° (-33°), and 40 cm to 210° (-24°).

2.4 Fuel Measurements

Two methods were used to estimate fuel loading: planar intercept transects and forest floor blocks. A measure of the down dead woody fuel loading was obtained by tallying fuel classes along planar intercept transects prior to the prescribed fires in January and February of 2003 and 2004? (Van Wagner, 1968; Brown, 1974). Woody fuels were tallied in four diameter size classes: 1) 1-hour timelag fuels, 0-0.635 cm, 2) 10-hour timelag fuels, 0.635-2.54 cm, 3) 100-hour timelag fuels, 2.54-7.62 cm, and 4) 1000-hour timelag fuels which included everything greater than 7.62 cm. Timelag fuel classes represent the amount of time required for a woody fuel to reflect changes in relative humidity (Fosberg et al., 1970). Thousand-hour fuels were initially separated into rotten and solid 1000-hour fuels, due to the expected differences in specific gravity (Brown, 1974). However, due to difficulty in determining condition class during the winter when wet logs were frozen, 1000-hour woody fuels were combined. Sampling lengths were chosen based on recommendations by Brown (1974). Fuel classes were nested along two 17 m transects with 1-hour and 10-hour timelag fuels tallied along two meters, 100-hour timelag fuels tallied along four meters, and 1000-hour rotten and solid timelag fuel diameters measured along the full seventeen meters. Transects were perpendicular to each other and located at opposite ends of each plot in locations that received little disturbance during the installation of the plots and during initial measurements of overstory trees. Woody fuel load weight (w) was calculated by first converting the number of intersections tallied to tons/acre for size classes using Brown's (1974) formulas:

$$w \text{ (tons/acre)} = (11.64 * n * d^2 * s * a * c)/ L) \quad \text{for 1-, 10-, and 100-hour fuels}$$

$$w \text{ (tons/acre)} = (11.64 * \sum d^2 * s * a * c)/ L) \quad \text{for 1000 hour fuels}$$

where n = number of intersections for the size class

d^2 = quadratic mean diameter for each timelag class obtained from Brown and Roussopoulos (1974)

$\sum d^2$ = summation of squared diameters s = specific gravity of each timelag class obtained from Anderson (1978)

a = nonhorizontal correction factor for fuel particles by timelag class obtained from Brown (1974)

c = slope correction factor for the transect = $\sqrt{1 + [\text{Percent slope}/100]^2}$

L = length of the sampling plane.

After obtaining weight in Tons/hectare, values were converted to Mg per hectare by multiplying by 2.2417.

A measure of forest floor mass was obtained in January and February 2003 by systematically collecting 0.073 m^2 (27 x 27 cm) sections of the forest floor from four locations located one meter from the boundary of each plot, adjacent to the planar intercept transects. The forest floor samples were removed from areas free of large woody material greater than 2.54 cm diameter in size to lessen the difficulty in collecting woody material within the square. When the predetermined location of a block crossed large wood, the block was moved the smallest distance necessary (regardless of direction) to an area free of woody material greater than 2.5 cm in diameter. The litter (Oi) layer was removed and bagged separately from the fermentation and humus layers (Oea). The material was dried at 60°C for 48 hours and then weighed. The combination of fermentation and humus is commonly referred to as "duff" in fuels-related literature (Brown, 1974) and the term will be used henceforth.

A heavy ice storm in February 2003 resulted in increased fuel loading on 18 plots, which included four fire-excluded and nine burn plots that had already been sampled. Therefore, dead woody fuel transects with fuel additions due to the ice storm were resampled in the same locations in March before the prescribed fires; forest floor blocks were not resampled.

Following the prescribed fires in March and April of 2003 (postburn) and after autumn leaf fall (post leaf fall) in January and February of 2004, four 27 x 27 cm forest floor blocks were systematically collected from locations one meter away from the pre-burn sample (winter 2003) in a predetermined direction. Again, the litter layer was removed and bagged separately from the fermentation and humus layers, and the material was dried at 60°C for 48 hours before being weighed. The postburn and post-leaf fall planar intercept transects were resampled in the same location as the preburn transects.

2.5 Statistical Analysis

Statistical analysis was based on 91 plots. Mean fuel load values for each plot were analyzed using a repeated measures, split-plot analysis in PROC MIXED in SAS (SAS Institute., 1999). Fixed effects included plot, treatment (burned or fire-excluded), time of measurement (preburn, postburn, and post leaf fall), and landscape position. Site was also included in the model as a random effect. Six fuel components and their sum were tested with the model. These components included leaf litter, duff (Oea), and the one-, ten-, 100-, and 1000-hour timelag woody fuel classes. Each fuel component was modeled separately to test for seven effects: treatment, time, landscape position, the interaction of treatment and sample period, the interaction of treatment and landscape position, the interaction of landscape position and sample period, and the interaction of treatment, landscape position, and sample period. Pairwise t-tests of predicted means were used to determine significant differences between treatments, landscape positions, and time (SAS Institute., 1999) with p-values less than 0.05 considered significant.

Analysis of variance (ANOVA) was used to determine if there were significant effects of site (n=3) and site-by-treatment interactions on the fuel load components on preburn fuel loads. Analysis of variance was also used to test for differences in the coefficient of variation of the plot litter mass between treatment and sampling period. Again, pairwise t-tests of predicted means were used to determine significant differences between study sites and treatments (SAS Institute., 1999).

3. Results

3.1 Fuel Characterization

Mean preburn fuel load on all plots averaged 40.4 ± 1.7 Mg/ha (n=91) and was highly variable with a standard deviation of 16.4 Mg/ha. The largest component of the fuel bed was duff (Oea), with a mean mass of 19.5 ± 0.7 Mg/ha, followed by 1000-hour (9.6 ± 1.4 Mg/ha) and 100-hour (4.9 ± 0.4 Mg/ha) woody fuels. Together duff, 100-, and 1000-hour fuels comprised approximately 84% of the total fuel load. The smallest component of the fuel load was 1-hour fuels (1.4%) with a mean mass of only 0.6 ± 0.04 Mg/ha, while litter fuels comprised 7.7% of the total fuel load with 3.1 ± 0.08 Mg/ha and 10-hour fuels comprised another 6.6%, with a mean mass of 2.7 ± 0.2 Mg/ha.

Duff and 1000-hour fuels were the only two fuel components that differed by landscape position (p=0.002 and p=0.009, respectively; Figure 1). Mesic plots (n=25) had the highest 1000-hr fuel loading (16.5 ± 4.3 Mg/ha), compared to 5.8 ± 1.6 Mg/ha on xeric plots (n=24), and 7.7 ± 1.2 Mg/ha on intermediate plots (n=42). Xeric plots had the highest amount of duff (23.1 ±

1.0 Mg/ha) compared to 18.6 ± 1.5 Mg/ha on mesic plots and 17.9 ± 0.9 Mg/ha on the intermediate plots. Total fuel load also varied significantly ($p<0.009$) by landscape position with mesic plots having a higher mean mass (45.3 ± 4.8 Mg/ha) than intermediate plots (37.8 ± 1.9 Mg/ha). Mean total mass on xeric plots (39.8 ± 2.5 Mg/ha) did not differ from the total fuel load on intermediate or xeric plots. Total fuel load also differed by site ($p=0.0004$) with the highest fuel loading on the Buck Creek (48.5 ± 3.3 Mg/ha, n=33), compared to 33.8 Mg/ha (± 2.1, n=28) on Chestnut Cliffs and 37.7 Mg/ha (± 2.5, n=30) on Wolfpen. Buck Creek also had significantly more 10- and 1000-hour fuel mass than Wolfpen and Chestnut Cliffs ($p=0.005$ and $p=0.0167$, respectively). Litter, 1-hour, and 100-hour woody fuels did not vary by landscape position or site (Figures 1 & 2).

3.2 Postburn fuel reduction

Of the individual fuel components analyzed with the repeated measures split-plot analysis, only litter, 1-, and 10-hour fuels were reduced by prescribed fire, with litter having the highest percent reduction of the individual fuel loads (Table 3). There was both a significant effect of time ($p<0.001$) and an interaction of time by treatment ($p=0.008$) on litter fuels, with a reduction occurring between pre- and post-burn measurements regardless of treatment. Litter decreased by over 98% ($p<0.0001$) from 3.2 to 0.4 Mg/ha on the burn treatments, and from 2.9 to 2.0 Mg/ha ($p<0.0001$), or 30%, on the fire-excluded treatments. This resulted in a 68 percent difference in litter reduction between treatments, which is attributable to the effect of fire (Figure 3). The high reduction of litter from fire-excluded sites could mean that as much as 31% of the reduction in litter on the burn treatments was the result of decomposition occurring between the pre and postburn sampling periods. Unfortunately it was not possible to correct the mean litter loss for decomposition on the burned plots due to the variability in mean litter loss between plots and within sites and landscape positions on fire-excluded treatment units.

An effect of treatment by time ($p=0.01$) was seen on 1-hour fuels. One hour woody fuels lost 0.12 Mg/ha, or 20%, of their preburn mass on burn treatments (Figure 4). There was not a significant effect of time by treatment on 10-hour fuels, but there was an interaction ($p<0.02$) between time, treatment, and landscape position (Figure 5). Although there were no significant differences between these landscape positions before the prescribed fires, postburn xeric plots (1.4 ± 0.23 Mg/ha) had less 10-hour fuel mass than both postburn intermediate plots (2.3 ± 0.33 Mg/ha, $p=0.0279$) and postburn mesic plots (3.2 ± 0.43 Mg/ha, $p=0.0007$).

The repeated measures split-plot analysis did not detect a significant postburn reduction in duff (Figure 6). Likewise, changes in 100- or 1000-hour timelag fuel loads were not significant (Figures 7 and 8, respectively).

3.3 Post leaf fall fuel load

When all three fuel load measurements (time) were included in the repeated measures analysis, there was again a significant effect of time and of time by treatment on leaf litter fuel loads. Litter mass on all sites was lower in the immediate postburn sampling period compared to the preburn ($p<0.0001$) and post leaf fall ($p<0.0001$) sampling periods (Figure 3). Preburn and post leaf fall litter mass were similar ($p=0.6$), possibly indicating that litter fuels returned to preburn levels. However, the effect of time was based on mean plot values from both the burned and fire-excluded treatments, and therefore treatment can not be determined.

Time (sampling period) effects were significant for three fuel load components: duff, 10-hour, and 1000-hour. Both preburn and postburn mean duff loads were higher than post leaf fall loads ($p=0.0037$ and $p=0.0069$ respectively). This effect of reduced duff in the post leaf fall sampling period was found on control and burn treatments (Figure 6). Post leaf fall, the mean 10-hour fuel mass (3.17 ± 0.2 Mg/ha) was significantly higher than preburn (2.72 ± 0.2, $p=0.04$) and postburn (2.3 ± 0.16 Mg/ha, $p<0.0001$) mean loading across all sites and treatment. Mean post leaf fall measurements of 1000-hour fuels were also greater, 13.30 ± 1.91 Mg/ha, than preburn (9.63 ± 1.43 Mg/ha, $p<0.0487$) and postburn (8.42 ± 1.13 Mg/ha, $p=0.0003$) mean loading across all sites and treatments, although there was not a difference between pre and post burn 1000-hour mean fuel loading ($p=0.2$).

An effect of time by treatment was seen again on 1-hour fuels. The reduction of mean 1-hour fuel load postburn ($p=0.0295$) on the burn treatments immediately following fire did not last. One-hour fuels increased ($p=0.008$) between the postburn and post leaf fall measurements, with post leaf fall fuel loads similar to preburn loading ($p=0.95$) on the burn treatments (Figure 4).

Landscape position also affected post leaf fall 1000-hour, duff, and total fuel loads, similar to pre-burn conditions. Mesic stands again had more 1000-hour time lag fuels than intermediate and xeric plots ($p=0.02$ and $p=0.017$) respectively. The analysis of all three sampling times showed that there was a significant effect of landscape position on duff fuel loads. Intermediate plots had less duff than mesic and xeric plots ($p=0.015$ and $p=0.0003$ respectively); xeric plots still had the greatest duff mass regardless of treatment.

Again, there were no significant effects of landscape position, time, or treatment on 100-hour fuels. There were also no significant effects of treatment by landscape position or time by landscape positions were found on total fuel load or on any of the 6 fuel components.

4. Discussion

4.1 Fuel Characterization

Direct comparison of total fuel loads to other studies is partially hampered by the differences in sampling methods used (Vose and Swank, 1993; Franklin et al., 1995; Hubbard et al., 2004). However, the use of Brown's planar intercept transects is being used to measure fuels in eastern deciduous forests with increasing frequency. Hartman (2004) and Kolaks et al. (2004) quantified preburn fuel loading in oak-hickory and oak-pine Ozark woodlands in southeastern Missouri using Brown's planar intercept transect and forest floor blocks, although they did not collect duff or include it as a component in their total fuel load estimates. Hartman (2004) found preburn fuel loads on his study sites ranging from 14.8 to 24.4 Mg/ha, while Kolaks et al. (2004) found fuel loads ranging from 15.2 to 19.3 Mg/ha. Removing mean duff mass from the total fuel load estimate in this study reduced my estimate to 20.9 Mg/ha, which is comparable to that found by Hartman (2004) and Kolaks et al. (2004). Franklin et al. (1995) also used Brown's planar intercept transects to sample down woody debris in oak stands in the Land Between the Lakes National Recreation Area in western Kentucky and Tennessee and found mean woody fuel loading of 13.5 Mg/ha, which is slightly lower than my total woody fuel loading of 17.8 ± 1.5 Mg/ha. Wendel and Smith (1986) estimated preburn woody fuels at 28 ± 14.2 Mg/ha in an oak-hickory stand in West Virginia, over a third more woody fuel than on my sites but still comparable due to the large standard error.

Litter and duff masses on my sites were within the range reported by others. Kolaks et al. (2004) reported a mean litter fuel load of approximately 6.7 Mg/ha, more than double what I found, while Wendel and Smith (1986) found preburn litter fuels averaging 9.8 ± 1.7 Mg/ha, or over three times more litter than on my site. In contrast, Franklin et al. (1995) reported mean preburn litter mass (1.5 Mg/ha) and duff (6.9 Mg/ha) masses half as large as on my sites. However, Franklin et al. (1995) calculated litter and duff weights by sampling a 1 m^2 plot and then visually estimating mass on 5 additional 1 m^2 plots as a percent of the plot collected as described in (Brown et al., 1982). Due to the high variability in litter and duff depths found in this study, visually estimating mass accurately would be difficult. Although differences in litter mass were not found between the three landscape positions in this study, downslope movement of litter has been reported for hardwood stands on steep slopes (Orndorff and Lang, 1981;

Boerner and Kooser, 1989). Leaf movement downslope could potentially increase forest floor mass on the mesic plots because of the additional input of litter due to their typically low slope position.

The higher accumulation of duff on the xeric plots in comparison to the mesic and intermediate plots was expected. High duff mass on xeric sites may be the result of limited decomposition due to low moisture availability and lower litter quality (Mudrick et al., 1994; Brady and Weil, 2002). Leaves generally decompose more rapidly on north-facing slopes than on south-facing slopes because of higher moisture retention on north slopes (Mudrick et al., 1994); the majority of the mesic plots had northerly to northeasterly aspects. Low quality litter has a high C/N ratio which limits bacterial and fungal growth (Brady and Weil, 2002). Forest floor accumulation and decomposition rate is affected by species composition. Many species found on xeric sites from oak and ericaceous species such as blueberry (*Vaccinium* spp.) have high lignin content in their litter often leading to slower decomposition than leaves with low lignin content and a low C/N ratio, such as sugar maple and yellow-poplar (*Liriodendron tulipifera* L.) (Melillo et al., 1982; Mudrick et al., 1994). Oak species were most abundant on our xeric plots which may have resulted in slower decomposition and more humus. Earthworm activity on plots with moist and non-sandy soils may have resulted in lower humus accumulation on mesic and intermediate sites as compared to the drier and rockier xeric plots (Brady and Weil, 2002). While earthworm abundance was not measured on each plot, earthworms were encountered more often on intermediate and mesic plots. Therefore, higher decomposition rates, higher quality litter, and higher earthworm activity on mesic sites probably resulted in less duff accumulation (Mudrick et al., 1994; Brady and Weil, 2002). Mader et al. (1977) reported higher fermentation and humus amounts on steep slopes in northern hardwood, which they attributed to slower decomposition rates and less incorporation into the A_1 horizon. Mader et al. (1977) also found that the weight of litter (Oi) and fermentation (Oe) layers decreased on wetter soils, while humus (Oa) accumulation was not related to soil drainage.

Our finding that 1000-hour fuels were highest on mesic plots coincides with previous findings of higher coarse woody debris amounts on lower slope positions (Harmon, 1984; Kolaks et al., 2003; Rubino and McCarthy, 2003). Kolaks et al. (2003) found that 1000-hour solid fuels were greater on protected slopes, compared to ridges and exposed slopes. "Protected slopes" is comparable to our "mesic" plot categorization, as the majority of our mesic plots were on north to northeast-facing slopes or in positions with hillshading from nearby ridges. Higher amounts of large woody fuels accumulate on low slope positions in topographically dissected landscapes due to dead logs falling and moving downslope (Harmon et al., 1986; Rubino and McCarthy, 2003). Higher aboveground productivity and biomass of mesic areas resulting from higher moisture and nutrient availability also contributes to higher woody debris mass in low slope positions (Rubino and McCarthy, 2003).

4.2 Fuel Reduction

Our finding of statistically significant reductions in the fine fuel components, litter and 1-hour fuels, compliments previous reports of fuel reductions in southern Appalachian and central hardwood forests (Wendel and Smith, 1986; Franklin et al., 1995; Clinton et al., 1998; Hubbard et al., 2004; Kolaks et al., 2004). Kolaks et al. (2004) reported that fuel consumption of woody fuels by prescribed fires on oak-hickory sites in Missouri decreased as timelag size class increased with significant reductions in litter, 1-, and 10- hour fuels. In a prescribed fire in a mixed white pine-hardwood stand in North Carolina, Clinton et al. (1998) found that the mass of litter and small wood (< 8 cm diameter) was reduced by 50 percent, and the humus layer was reduced by 20 percent; however, wood larger than 8 cm was not sampled. After a single prescribed fire in southern Ohio, Riccardi and McCarthy (2002) found that the litter and duff were significantly decreased compared to a fire excluded control treatment. They found no change in 10-hour fuel on the burn treatment, but a significant increase in 100-hour woody fuels following burning. We did not see a similar increase, but in contrast found that the mean mass of 100-hour fuels on our burn treatment decreased from 5.26 to 4.37 Mg/ha post burn, although the reduction was not statistically significant, and 100-hour fuel loads returned to preburn levels (5.34 Mg/ha) by the post leaf fall measurements (Figure 7). Wendel and Smith (1986) reported a 56% reduction in litter fuels and of 18% in 1- and 10-hour woody fuels combined, following a prescribed fire in West Virginia; however, there was only one burn treatment in their study so statistical significance can not be applied.

Kolaks et al. (2004) found decreases in 100- and 1000-hour fuels similar in magnitude to those observed on my sites, however these reductions were not significant at $p<0.05$ on their sites either. They also found that consumption did not vary significantly among aspects (ridge, protected, exposed) although the reduction of 1000-hour fuels was greater on slopes than on ridges as slope steepness can affect fire intensity (Franklin et al., 1997). Kolaks et al. (2004) attributed the higher consumption on slopes to increased fire behavior as compared to flat ridges where fire behavior is mainly wind driven. In a western Kentucky prescribed burn, fire temperatures were primarily influenced by the amount of litter and duff present in spots where the slope was less than 20 degrees, but the steepness of the slope had a greater affect on the fire temperatures than the amount of fuel present when the slope was greater than 20 degrees (Franklin et al., 1997).

High variability in our data may have prevented us from detecting changes in 10, 100- and 1000-hr fuels. Our approach of sampling and averaging two transects on 8 to12 plots per treatment unit was comparable Kolaks et al. (2004) sampling of 1 transect at 15 points in a treatment unit. While Wendel and Smith's (1986) sampled 19 transects on one unreplicated burn unit, the standard error of their reduction was still greater than one half their mean reduction. Our sampling scheme was less intense than Riccardi and McCarthy's (2002), who sampled two transects at 36 points per 20 hectare treatment unit. Based on our standard deviations and the mean reductions observed, power analysis in SAS estimated we would need to have 128 sampling units to have a power of 0.80 for detecting a significant reduction in 100-hour woody fuels if one had occurred. In this study we had approximately 20 sampling units in each burn site and approximately 10 in each fire-excluded site, for a total of 62 and 31 sampling units for each treatment. In the future, I recommend tallying 10- and 100-hour fuels along 4 and 8 meter transects (double the length used) in order to reduce variability in estimated total fuel loading and fuel reduction. Additions of dead wood during the ice storm damage also may have negatively impacted fuel consumption on those plots due to the greenness of the wood, as evident by the growth and opening of many leaf buds on fallen yellow poplar (*Lirodendron tulipifera* L.) limbs during the spring of 2003 on fire-excluded plots.

The trend of duff reduction (Figure 6) may partially be due to the actual reduction or loss of the fermentation layer (Oe) by burning, and partially the result of sampling error. Preburn samples were collected in cold weather and occasionally when the ground was frozen, making it difficult to meticulously separate the imbedded mineral soil from the duff. This may have led to the incorporation of the A horizon into our humus layer. Improved separation during humus collection almost certainly accounted for the consistently lower duff mass in the post leaf fall samples across all treatments. Percent loss of organic matter by ignition was unfortunately not calculated for the fermentation and humus samples.

While only 19% of the mean total fuel load on the burn plots (n=62) was reduced (41.9 to 33.8 Mg/ha), the immediate threat of wildfires may have been reduced through disruption of fuel bed continuity. Analysis of variance showed that the coefficient of variation of the litter mass for individual plots was higher on the burn treatment during the post leaf fall sampling period compared to the preburn sampling period (p=0.016), possibly due to a less continuous fuel bed. Van Lear and Waldrop (1989) reported that after a hazard-reduction burn in the Appalachians, stands were usually protected from wildfire until the next leaf fall, and the threat of wildfires was minor for three to seven years afterward. However, hardwood forests have been annually burned in studies in Tennessee, Missouri, and Minnesota (Thor and Nichols, 1973; White, 1983; Huddle and Pallardy, 1996). After seven years, Thor and Nichols (1973) found that annually burned hardwood stands had lower leaf litter weights (2.5 Mg/ha) than unburned hardwood stands (6.8 Mg/ha) in Tennessee. Unfortunately little information is available on the long term effects of burning on woody fuels (Loomis and Crosby, 1970; Hartman, 2004).

We found that eastern wild turkeys (*Meleagris gallopavo silvestris*) inhabiting the study sites increased forest floor variability and therefore the continuity of the fuel bed on our study sites. Patches of forest floor, approximately one half to greater than 20 meters, showed evidence of turkeys having scraped the litter and fermentation layers off, exposing humus and mineral soil. The resulting piles of litter, fermentation and humus made collecting forest floor samples difficult and may have accelerated litter decomposition through the burial of recently fallen leaves. The burial and mixing may have increased moisture and contact with decomposers allowing soil fauna to more quickly decompose the leaves.

The selective consumption of certain fuel components during a prescribed fire has many ecological implications. While 1000-hour time lag fuels and duff comprise a large portion of the total fuel load, it is important ecologically that they were not significantly reduced on our study sites. Large woody fuels, also known as coarse woody debris, have importance to wildlife (Harmon et al., 1986). For example, Williams (1936) found high use of downed logs by many forest birds due to the high insect numbers associated with decaying logs. Numbers of small forest mammals, such as shrews (Insectivora: Soricidae), are also correlated with coarse woody debris abundance (Ford et al., 1997). The high retention of the humus on our study sites was also important as it should help maintain soil moisture and prevent soil erosion by maintaining soil porosity (Brady and Weil, 2002). Removal of the litter layer, without removal of the fermentation and humus layers, may also facilitate the establishment of oak seedlings. Garcia et al. (2002) found that buried acorns uncovered by litter had a higher probability of germinating and establishing as seedling than acorns buried and covered by litter.

5. Conclusions

Significant reduction in fuels occurred only in litter and one-hour fuels which are minor components of the fuel bed, comprising only 9% of total preburn fuel loading. Ten-hour fuels were also reduced, but only on xeric plots. Ten months after burning, litter and 1-hour fuel loads were not different than preburn levels. Fuel loading of duff and 1000-hour fuels varied topographically, but contributed little to fire intensity as they were not consumed. The high mass of duff may act as a buffer on xeric plots where fires would be expected to burn more intensely, and prevent high soil exposure. While I have only been able to compare immediate and 10 month post burn fuel loadings with preburn data, long term monitoring should yield interesting information on the effects of prescribed fire on fuel loading and composition, as well as the ecological impacts of burning.

Table 1: Total numbers of plots arranged by site, treatment, and landscape position. There are two treatments, burned and fire-excluded (FE), and three study sites: Chestnut Cliffs (CC), Buck Creek (BC), and Wolfpen (WP). Plots were classified into three landscape positions: mesic, intermediate, and xeric.

Treatment	**Mesic**	**Intermediate**	**Xeric**	**Total**
CC Burn	7	8	4	19
BC Burn	5	11	7	23
WP Burn	3	11	6	20
CC FE	2	5	2	9
BC FE	3	4	3	10
WP FE	5	3	2	10
Total	25	42	24	91

Table 2: Ambient conditions on day of burn and mean maximum temperature (°C) surpassed at three heights above forest floor (0, 20, and 40 cm) for the three study sites: Buck Creek (BC), Wolfpen (WP), and Chestnut Cliffs (CC). Chestnut Cliffs (south) and Chestnut Cliffs (north) are shown separately because they were burned on two different days. Ranges represent the mean maximum temperatures of individual plots within burn unit.

Conditions	**CC south**	**CC north**	**BC**	**WP**
Burn date	3/24/03	3/25/03	4/14/03	4/16/03
Time of ignition	1230	1130	1130	1230
Air temperature (°C)	24	26	21.5	28
Relative humidity (%)	39	31	36	36
Wind direction	W	SW	NW	W
Wind speed (km/hr)	0-9	3-11	0-2	4.8-6.4
10-hour fuel moisture (%)	18	14	15	11
Pyrometer	**CC south** (n=10)	**CC north** (n=8)	**BC** (n=23)	**WP** (n=20)
0 cm mean (°C)	474	533	522	575
Range	(87 – 536)	(374 – 617)	(43 – 644)	(469 – 644)
20 cm mean	233	316	229	313
Range	(115 – 359)	(87 – 536)	(67 – 466)	(150 – 550)
40 cm mean	158	234	165	225
Range	(49 – 269)	(49 – 442)	(63 – 353)	(97 – 370)

Table 3: Changes in fuel loading between preburn and immediately postburn sampling periods in 2003 on burned and fire-excluded treatments for six fuel components and the total fuel load, given in Mg/ha and as a percent of preburn fuel load. Asterisks denote significant changes at α = 0.05 level.

	Fuel Loading (Mg/ha)						
	Litter (Oi)	Duff (Oea)	1-hr	10-hr	100-hr	1000 hr	Total
Burned Treatment Δ	-2.8 * (87.8%)	-2.6 (12.9%)	-0.1 * (20.3%)	-0.6 (19.9%)	-0.9 (16.8%)	-1.2 (11.8%)	-8.12 (19.4%)
Mesic	-2.4 (75.2%)	+1.1 (6.0%)	+0.02 (4.3%)	+0.8 (34.0%)	+1.3 (29.0%)	-3.9 (20.8%)	-3.0 (6.2%)
Intermediate	-2.8 (89.9%)	-4.4 (23.0%)	-0.1 (22.2%)	-0.7 (22.7%)	-1.7 (28.4%)	-1.4 (16.6%)	-11.1 (27.7%)
Xeric	-3.2 (94.8%)	-2.8 (12.0%)	-0.2 (35.8%)	-1.6 (53.0%)	-1.3 (28.6%)	+1.6 (35.1%)	-7.4 (18.7%)
Fire-excluded Treatment Δ	-0.9 * (30.2%)	+0.5 (2.6%)	+0.1 * (21.0%)	-0.08 (3.2%)	-0.5 (11.5%)	-1.3 (14.3%)	-2.2 (5.9 %)
Mesic	-0.99 (34.1%)	+2.38 (13.4%)	+0.10 (23.6%)	-0.63 (23.6%)	+0.30 (7.9%)	-1.48 (11.1%)	-0.32 (0.8%)
Intermediate	-0.7 (25.4%)	+0.6 (3.9%)	+0.1 (19.7%)	+0.2 (9.9%)	-0.9 (20.4%)	-0.9 (13.0%)	-1.5 (4.7%)
Xeric	-1.0 (32.7%)	-2.5 (11.3%)	+0.1 (20.4%)	+0.2 (7.4%)	-0.9 (21.9%)	-2.0 (23.4%)	-6.0 (14.8%)

Figure 1: Components of preburn fuel load on the three landscape positions: mesic, intermediate, and xeric. Different lower case letters denote significant differences at $p<0.05$ between landscape position within fuel component. Different upper class letters denote significant differences in total fuel load at $p<0.05$ between landscape positions.

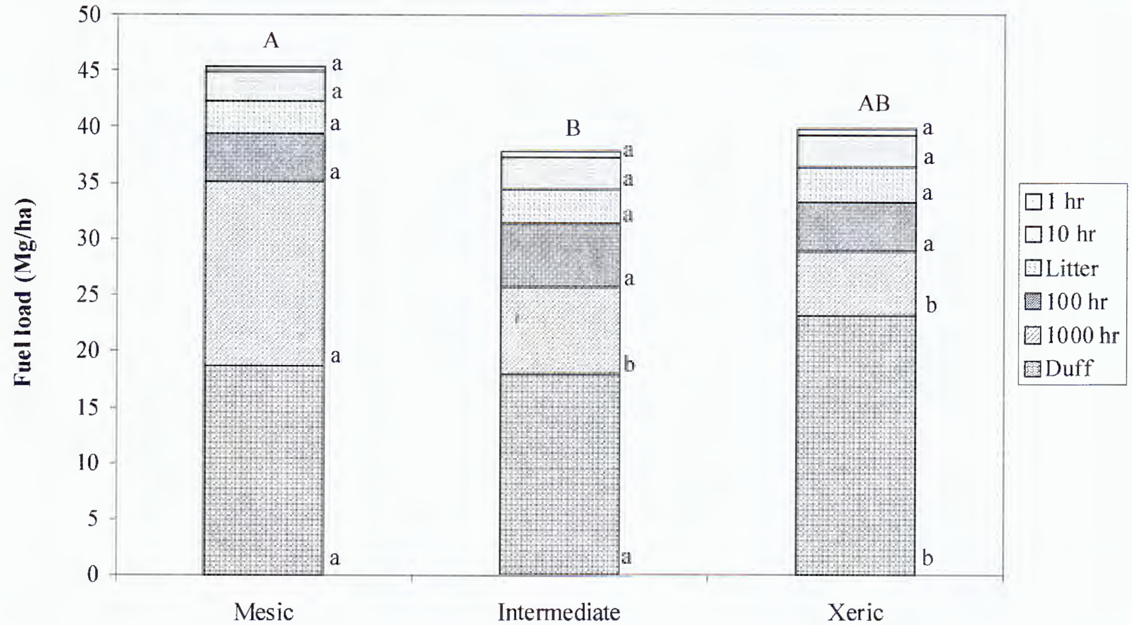


Figure 2: Preburn fuel load by component on each of the three study sites: Chestnut Cliffs (CC), Buck Creek (BC), and Wolfpen (WP). Different lower case letters denote significant differences at p<0.05 between sites within fuel component. Different upper class letters denote significant differences in total fuel at p<0.05 between sites.

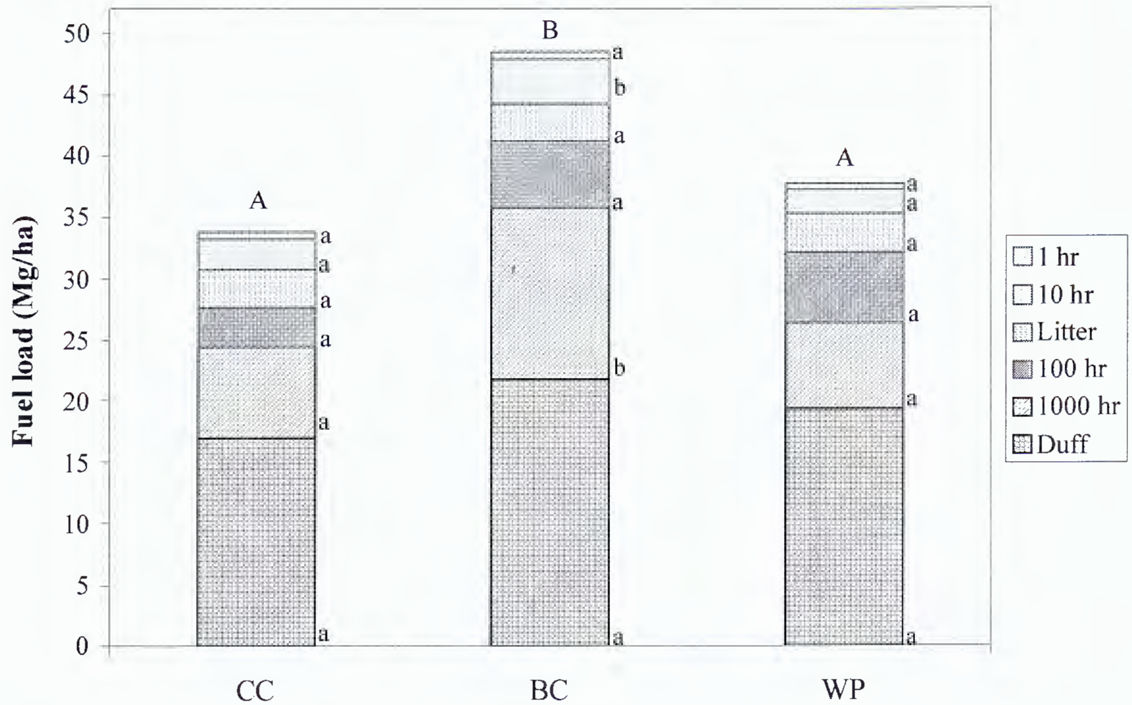


Figure 3: Mean litter fuel loads on burned and fire-excluded treatments before prescribed fires in 2003 (preburn), immediately after prescribed fires in 2003 (postburn), and 10 months after the prescribed fires (post leaf fall). Lower case Latin letters denote significant differences ($p<0.05$) in litter mass between sampling periods on the burned treatment units. Greek letters denote significant differences in litter mass between sampling periods on fire excluded treatment units.

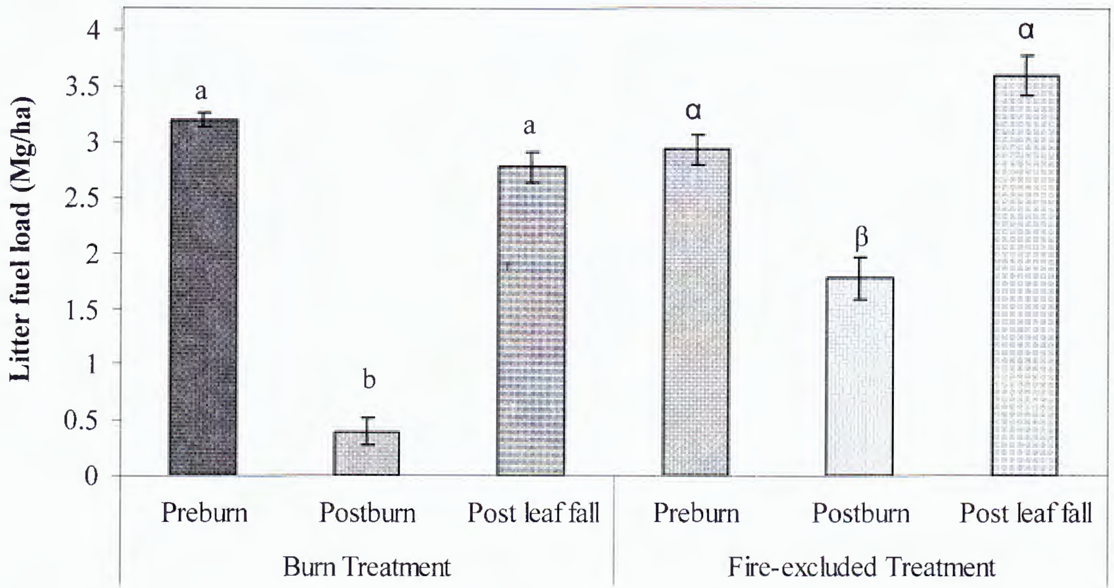


Figure 4: Mean 1-hour timelag woody fuel loads on burned and fire-excluded treatments before prescribed fires in 2003 (preburn), immediately after prescribed fires in 2003 (postburn), and 10 months after the prescribed fires (post leaf fall). Lower case Latin letters denote significant differences in 1-hour fuel mass ($p<0.05$).

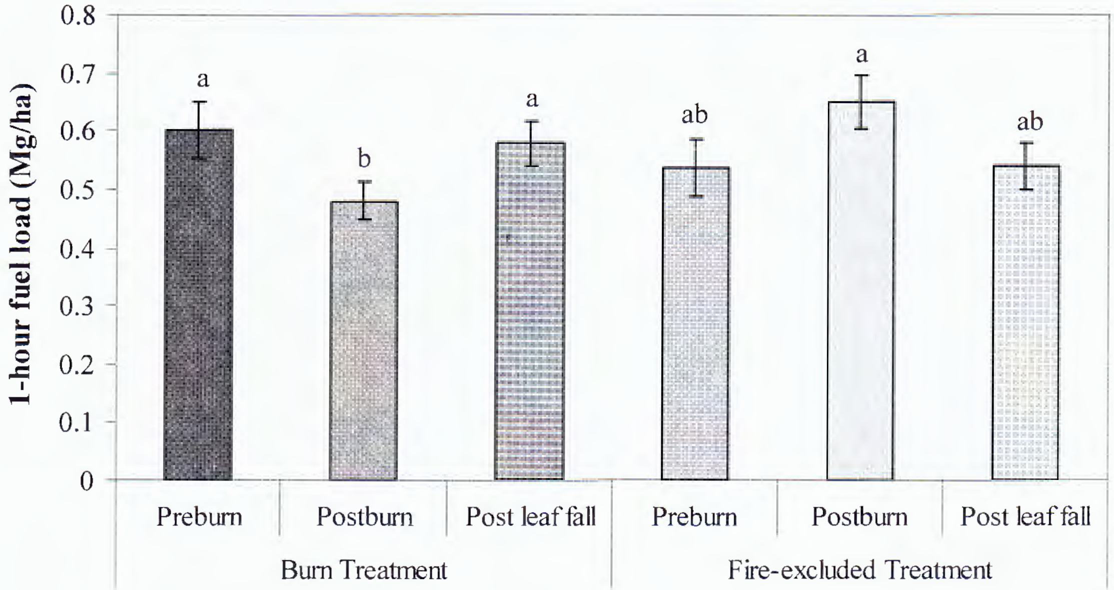


Figure 5: Mean 10-hour timelag woody fuel loads on burned and fire-excluded treatments before prescribed fires in 2003 (preburn), immediately after prescribed fires in 2003 (postburn), separated by landscape position (mesic, intermediate, and xeric). Different lower case letters denote significant differences ($p<0.05$) between mean 10-hour fuel loads at $p<0.05$ for landscape position by treatment and by time.

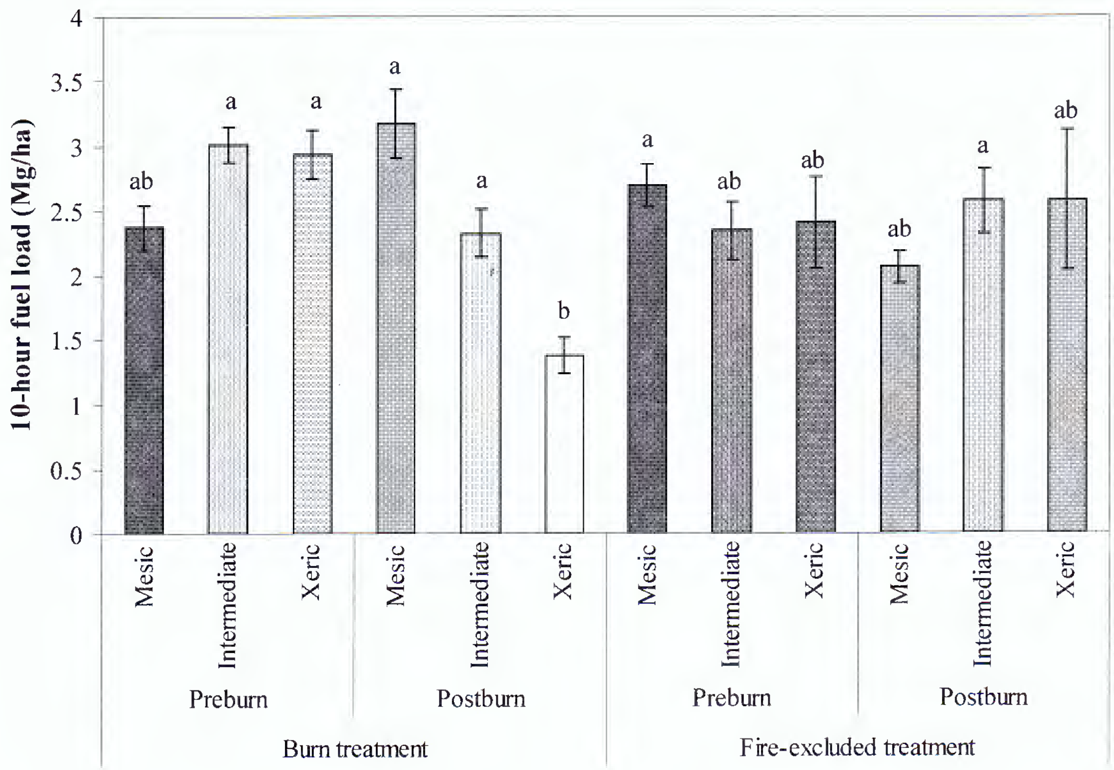


Figure 6: Mean duff (Oea) fuel loads on burned and fire-excluded treatments before prescribed fires in 2003 (preburn), immediately after prescribed fires in 2003 (postburn), and 10 months after the prescribed fires (post leaf fall). Lower case Latin letters denote significant differences in duff fuel mass. Greek letters denote significant differences ($p<0.05$) in litter mass between sampling periods on fire excluded treatment units.

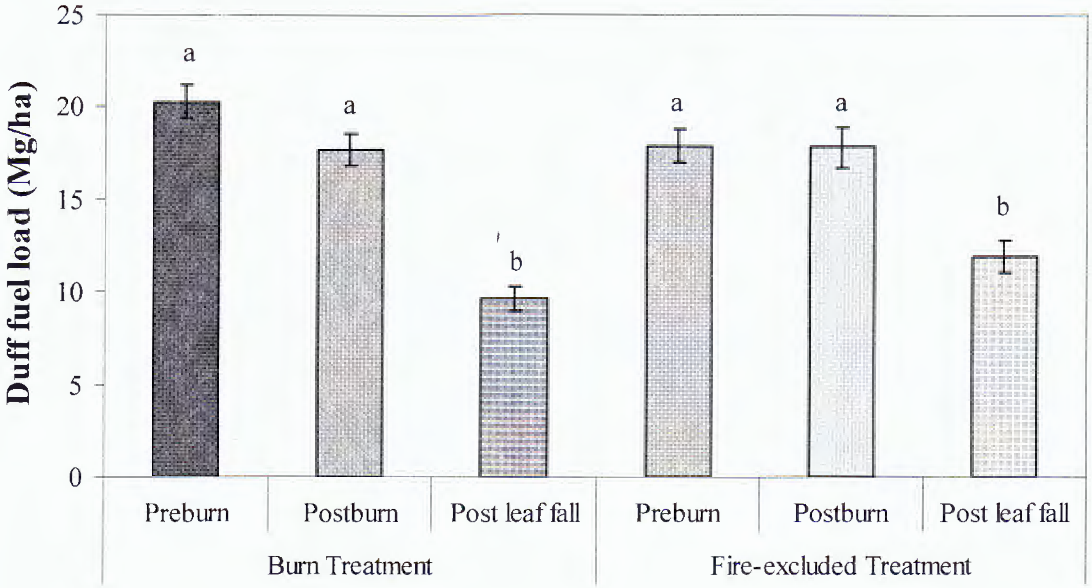


Figure 7: Mean 100-hour timelag woody fuel loads on burned and fire-excluded treatments before prescribed fires in 2003 (preburn), immediately after prescribed fires in 2003 (postburn), and 10 months after the prescribed fires (post leaf fall). There were no significant differences in 100-hour fuel mass ($p<0.05$).

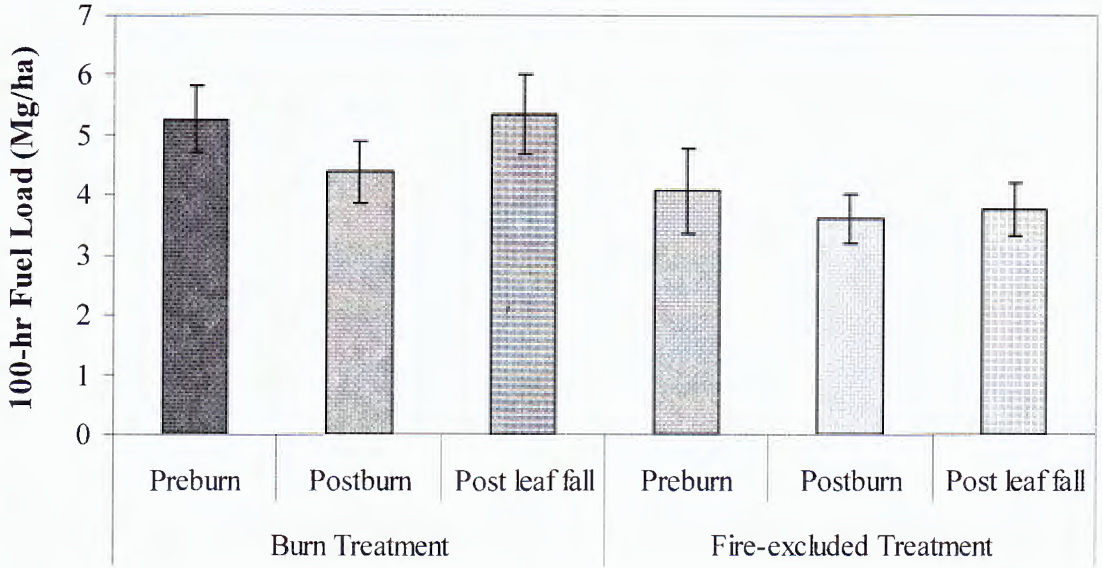
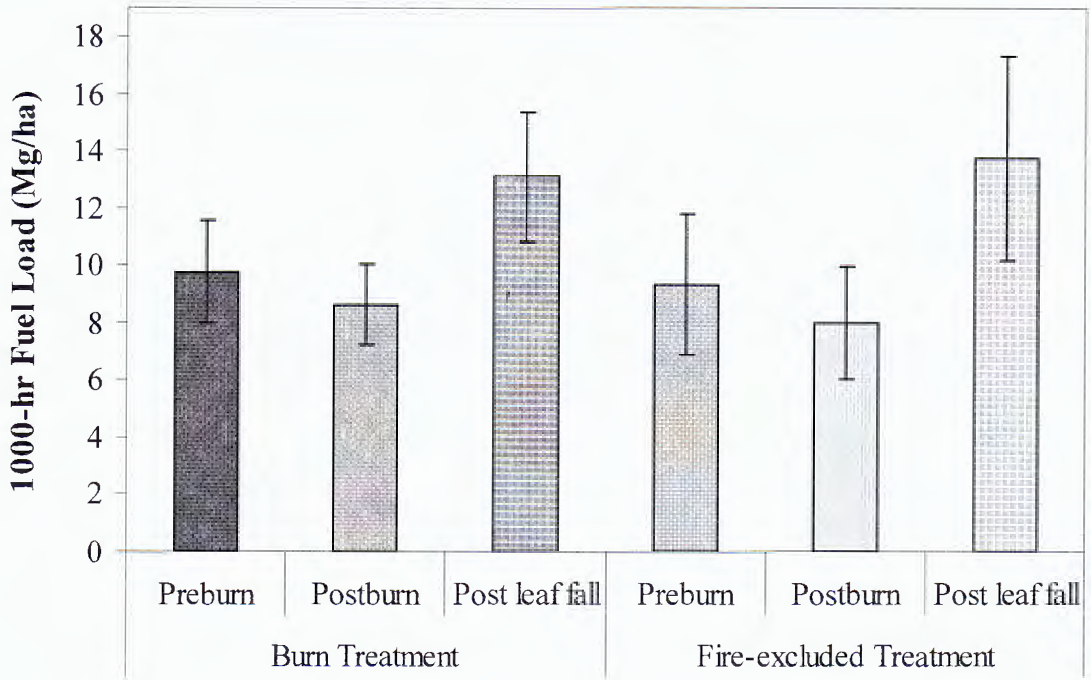


Figure 8: Mean 1000-hour timelag woody fuel loads on burned and fire-excluded treatments before prescribed fires in 2003 (preburn), immediately after prescribed fires in 2003 (postburn), and 10 months after the prescribed fires (post leaf fall). There were no significant differences in 1000-hour fuel mass ($p<0.05$).



CHAPTER THREE

Characterization and predictors of maximum bark scorch height and tree mortality after a single prescribed fire in a eastern hardwood forest, Kentucky

1. Introduction

While the perceived positive effects of prescribed fire include increased understory light levels, removal of competing vegetation, and reduction of fuel loading, damage to timber trees is a potential negative result (Van Lear and Waldrop, 1989), and is of considerable concern to some forest managers. Knowledge of tree damage caused during prescribed fires is important to forest managers because fire scars provide an entryway for fungal pathogens and insects, which can cause bole decay, and decrease merchantable values (Nelson et al., 1933). Tree damage is correlated with the duration of the exposure of cambium cells to lethal temperatures (55-60° C) during a fire (Fahnestock and Hare, 1964). Thick bark insulates the cambium from lethal temperatures. Bark thickness generally increases with tree age and size, although the insulating properties and thickness of bark vary among tree species at the same diameter (Hare, 1965; Harmon, 1984). Tree wounding and mortality depend on bark thickness, and also the extent to which the bole circumference is exposed to lethal temperatures. Small trees are typically killed by passing ground fires, so small wounded trees are rarely seen (Gutsell and Johnson, 1996). Fire scars form on the leeward side of trees, which is typically on the uphill side during a fire, because the tree blocks the wind and creates a pocket of still air which increases flame length and residency in comparison to the windward side (Gill, 1974; Gutsell and Johnson, 1996). Tree diameter affects the size of standing leeward flames, resulting in higher flames behind large trees (Gill, 1974; Gutsell and Johnson, 1996).

Bark scorch heights have been used for estimating bole wounding, tree mortality, and fire intensity for many decades (Nelson et al., 1933; Loomis, 1973; McNab, 1977; Cain, 1984; Menges and Deyrup, 2001). Bark scorch height is a measure of the discoloration on the outer bark on a tree bole after a fire has passed, and has also been referred to as "basal bole blackening" and "stem-bark char." Loomis (1973) described bark blackening, or bark scorch, as a visible manifestation of the duration and temperature a tree is exposed to during a fire. Using scorch heights measured after wildfires in an oak-hickory forest to develop equations for predicting tree mortality and wound dimensions, Loomis (1973) found that scorch height, diameter at breast height (DBH), and tree species are correlated with tree mortality. Diameter at breast height was found to be a good predictor of scorched tree mortality because of its relation to both bark thickness and tree height.

Low intensity prescribed fire has previously been found to have little effect on the survival of overstory trees (White, 1983; Rouse, 1986; Reich et al., 1990). However, Smith and Sutherland (1999) reported that a low intensity fire in southeastern Ohio caused wood discoloration and cambial cell death in overstory oak, although the wounds were not externally visible because the bark remained intact. Few studies have examined the effects of low intensity prescribed fire on wound formation in uncut eastern deciduous forests and further examination of the effects of fires are warranted, particularly in the face of increased burning.

This study was designed to evaluate the effects of woody debris and leaf litter accumulation adjacent to tree boles, fire temperature, topographic position, species, and DBH on bark scorch height on hardwood trees in an eastern Kentucky forest. Since accurate assessments of the effects of fire on bole wounding and tree mortality can only be made after several growing seasons have passed (Stickel, 1935; Loomis, 1973), mortality and wounding rates will be monitored annually and future research will test the correlation of mortality and wounding rates with bark scorch and the predictors of bark scorch. For this study, I hypothesized that 1) bark scorch heights vary by DBH because of the effect of diameter on flame characteristics (Gill, 1974), 2) bark scorch heights vary by tree species because of tree size and bark characteristics, and 3) maximum bark scorch heights are influenced by the position of trees on the landscape, fire behavior (measured as temperature), and fuel accumulation adjacent to tree boles and on a plot level.

2. Methods

2.1 Site Description

Three study sites were chosen within the Morehead Ranger District of the Daniel Boone National Forest (DBNF) in eastern Kentucky, Buck Creek (Menifee and Bath Counties), Chestnut Cliffs (Menifee County), and Wolfpen (Bath County). The study sites are between 194 and 293 ha, and are located within an 18 km^2 area. The mean annual temperature is 12.2 °C with mean daily maximum and minimum temperatures in January of 7 °C and -5 °C, and in July, 30 °C and 16.5°C (Hill, 1976). Mean annual precipitation is 109 cm spread evenly throughout the year, with approximately 38 cm of snowfall each winter (Hill, 1976). Elevation ranges from 260 to 360 m (850 to 1180 ft), and encompasses slopes of varying aspect in each study area. The topography consists of steep slopes and undulating topography which results in site conditions varying from submesic to xeric. Soils are variable in soil depth and texture due to the steep unglaciated topography and are classified as Typic Hapludults, Typic Hapludalfs, Ultic Hapludalfs, and Typic Dystrochrepts (Avers, 1974). Sites chosen are not known to have had fires of any kind on them during the last 30 years (Michael Colgan, U.S. Forest Service, Morehead, Ky., pers. com.).

2.2 Experimental Design

Each study site was subdivided into three treatments for use in a long term fire study of the effects of prescribed fire on oak regeneration at different frequencies: (1) 'frequent' prescribed fires, (2) 'infrequent' prescribed fires, and (3) fire-excluded. The treatment areas were 55 to 117 hectares, and contained 8 to12 plots that were systematically located from a grid overlaid on a topographic map for a total of 93 plots, with 30 to 33 plots per site. The plots were 10 by 40 meters and oriented parallel to the topographic contour. Plots were categorized into landscape positions (sub-xeric, intermediate, and sub-mesic) based on hill-shading, aspect, slope position, and species composition, resulting in a split-plot design. For simplicity, landscape positions will hereon be referred to as xeric, intermediate, and mesic.

The first prescribed fires in the frequent and infrequent treatment areas occurred in the spring of 2003. For this study the frequent and infrequent treatment sites were combined into one treatment unit, "burned," because only data from one year of fire is available. The combination of two treatment units into one resulted in an unbalanced design with approximately twice as many plots in the burned treatments as the fire-excluded treatment.

2.3 Fire prescription and temperature measurements

USDA Forest Service personnel of the DBNF conducted the prescribed fires in March and April of 2003, using drip torches and helicopter ignition. The Chestnut Cliff site was burned on two consecutive days, with the southern section burned first. Ambient weather conditions varied somewhat among and within sites (Table 2). Observations of flame heights and rates of spread were only made in a few locations due to obstacles encountered in measuring and recording these parameters on steep slopes during helicopter ignitions, so average flame heights and rates of spread are not known. Flame heights and rates of spread were highly variable within and between burn treatments due to ignition along lower slope, mid-slope, and ridge positions.

Fire temperature data have been recorded for prescribed fires and used as an empirical estimate of fire intensity (Cole et al., 1992; Franklin et al., 1997; Clinton et al., 1998; Blankenship and Arthur, 1999). Fire temperatures were recorded and used as a surrogate for fire intensity during the prescribed fires, since it was not possible to record flame length and rate of spread on our plots due to the large and topographically variable study sites and personnel safety concerns. Temperatures were measured using six pyrometers per plot, with three located along each of the two fuel transects. Six Tempilaq® fire sensitive paints representing temperature ranges from 79°C to 482°C were painted onto aluminum tags. Painted tags were attached to pin flag stakes at 20 and 40 cm above the forest floor and on the surface within ten days of the burn. Each tag was covered with a small piece of aluminum foil to prevent water damage and smoke discoloration. The melting point of aluminum at 644°C provided an additional maximum temperature. The pyrometers were collected within four days of the fires. Mean fire temperatures on each plot were calculated by averaging the highest temperature surpassed on each pyrometer. Temperatures were variable due to ignition intensity and four plots had fire on less than 25% of their total area. The first Chestnut Cliffs burn (March 24) had the lowest mean temperatures surpassed while the Wolfpen burn (April 16th) had the hottest mean temperatures (Table 1). Unfortunately, one plot in Chestnut Cliffs (north) did not have pyrometers in place before the prescribed fires, and strangely, less than 10 percent of this plot burned. The omission of temperature measurements on this plot resulted in an erroneously high temperature range and mean maximum temperature for the Chestnut Cliffs (north) burn. Including ambient temperatures for the omitted plot reduces mean maximum temperature by a different amount for each height position with 0 cm reducing to 476° (-57°), 20 cm to 283° (-33°), and 40 cm to 210° (-24°).

2.4 Tree condition measurements

During the summer of 2002, prior to the burns, all overstory trees (≥10 cm dbh) were tagged, measured, and mapped within each plot. Midstory trees (>2.5 cm and <10 cm at dbh) were tagged and measured in one quarter of each plot, 100 m^2. Standing dead trees were also noted, tagged, and measured. Crown condition for overstory trees was rated on a scale of 1 to 3, with 3 representing less than 25% dieback, 2 representing 25-50% dieback, 1 representing 50-75% dieback, and dead trees recoded as 0 (Gottschalk and MacFarlane, 1993). Crown defoliation of oaks (*Quercus* spp.) by caterpillars, including the forest tent caterpillars (*Malcosoma disstria*), linden looper (*Erannis tiliaria*), and common oak moth (*Phoberia atomaris*), occurred on the study sites (Townsend, 2002; Townsend, 2004; Jeffrey Lewis, U.S. Forest Service, Morehead, KY., pers.com.); trees that were heavily defoliated were simply recorded as "defoliated." During the summer of 2003, tagged trees were re-measured and re-evaluated for crown condition. In May of 2003, the height of maximum bark scorch, minimum scorch height, total width of the scorch at the tree base, width of scorch at 30 cm above the ground (Loomis, 1973), and location of the highest point of scorch in relation to hillslope (Smith and Sutherland, 1999) were recorded for 1558 tagged trees.

2.5 Wood and litter presence

To better understand the causes of fire damage, the presence of woody debris and depth of leaf litter near the tree bases were recorded during the summer of 2002. Leaf litter was visually categorized as absent, moderate (greater than 1 cm around at least a quarter of the tree base), or plentiful (greater than 7 centimeter deep around at least a quarter of the tree base.) Down wood presence was recorded if downed wood greater than 7.6 cm in diameter was within 30 cm of a tree stem, resulting in a present/absent data structure. The criterion for down wood was established by modifying the methods of Brose and Van Lear (1999), who recorded the presence of 1-5 pieces of branch wood greater than 7.6 cm within 90 cm of a tree base as being a moderate amount of slash.

2.6 Fuel consumption

Before the prescribed fires during January and February of 2003, four 27x27 cm segments of the forest floor (Oiea) were systematically collected from fixed locations one meter from the boundary of each plot. Samples were removed from areas free of large woody material (> 2.54 cm diameter) in order to lessen the difficulty in collecting woody material within the square. When the predetermined location of a forest floor block intercepted large wood, the block was moved the smallest distance necessary (regardless of direction) to a large wood-free area. The litter (Oi) layer was removed and bagged separately from the fermentation and humus layers (Oea). The material was dried at 60° C for at least 48 hours and then weighed. After the prescribed fires, within 4 weeks, 4 more samples of the forest floor were collected within 1 meter of the preburn sample using the same method.

2.7 Statistical Analysis

A regression model with class variables was used to determine predictors of maximum bark scorch height on the burn treatments using PROC GLM (SAS Institute., 1999). The GLM procedure in SAS was used for the regression model as it automatically generates dummy variables for the class variables (SAS Institute., 1999). Continuous variables tested included DBH; mean maximum fire temperatures at 0, 20, and 40 cm from the litter surface; slope; total mass of the litter layer (including leaves, wood, bark, and seeds) pre- and postburn; litter layer mass lost between sampling periods; total leaf mass (leaves only) pre- and postburn; and leaf mass lost between sampling periods. Class variables included site, species, landscape position, diameter (cm) grouped into 8 classes (2.5-4.9, 5-9.9, 10-14.9, 15-19.9, 20-29.9, 30-39.9, 40-49.9, 50-85), litter accumulation, wood presence, and percent slope grouped into 5 classes (0-15, 16-30, 30-45, 45-60, and 61-75). The dependent variable, maximum scorch height, was logarithmically transformed to stabilize variances (Kuehl, 1994). To avoid the omission of trees without scorch, I added a fixed number to all values before log transformation. However, the normal probability plot of the residuals showed that the data were still not meeting the normal distribution assumptions due to the high number of unscorched trees (262 out of 1558). Therefore, analyses of the original log transformed data that omitted unscorched trees is shown here.

Inferences of the effect of bark char on tree health were made using correlation in PROC CORR and logistic regression in PROC LOGISTIC (SAS Institute., 1999). The effect of prescribed fire on tree mortality was compared to mortality of trees on the fire-excluded treatments for 8 diameter size classes with an ANOVA procedure in PROC GLM, with pairwise t-tests of predicted means used to determine significant differences between treatments (SAS Institute., 1999).

3. Results

3.1 Percentage of trees scorched

Eighty-two percent of the trees in our burn treatment were scorched during the prescribed fires, with maximum point of scorch predominately (>80%) found on the uphill side of the trunk. Beech had the lowest percentage of trees with scorch (62.5%), followed closely by white oak (*Quercus alba* L.) with 64%, then sugar maple (*Acer saccharum* Marsh.) with 69%, and hickories (*Carya* spp.) with 75%. At least 80% of all other species were scorched, with sourwood (*Oxydendrum arboreum*, (L.) DC.) and sassafras (*Sassafras albidum* (Nutt.) Ness) having the highest proportion of individuals scorched, 92.7% and 92.3% respectively. The

Wolfpen plots had the highest proportion of scorched trees (88.7 %), while Buck Creek had 85.5 percent scorched and Chestnut Cliffs had only 72.7 percent of the trees scorched. There was not a clear pattern in the proportion of trees scorched by dbh class.

3.2 Predictors of maximum bark scorch height

Maximum bark scorch height was selected as the dependent variable for all statistical analyses because it is less subjective than average scorch height; many of the trees were not scorched along their entire circumference (62%) biasing mean minimum scorch height values; and width of scorching was confounded by tree diameter.

Nine of our independent variables and four interaction effects were significant predictors of bark scorch (Table 2) ($F = 23.04$; $R^2 = 0.55$). Diameter at breast height was a significant predictor of maximum bark scorch height when it was included in the model as a continuous variable ($p<0.0001$) and as a class variable ($p<0.0001$) with trees grouped into 8 size classes. Mean scorch heights increased as diameter size class increased (Figure 1). To determine the effect of species on scorch height, eighteen species or species groups were included in the statistical model, with unequal numbers of trees in each group (Table 3). All trees were included in the model, but some species were collapsed into species groups, such as hickories and an 'other' category, which included all species with fewer than 20 trees with the exception of yellow pine (*Pinus* spp.). 'Species,' defined in this way, was a significant predictor of maximum bark scorch height ($p<0.0001$). Species with smooth bark, such as red maple (*A. rubrum* L.), tended to have lower mean scorch heights than species with rough bark, such as black oak (*Quercus velutina* Lam.) (Figure 2). Smaller, understory species, such as flowering dogwood (*Cornus florida* L.) and downy serviceberry (*Amelanchier arborea* [Michx.] Fern), also had lower mean maximum scorch heights. However, there was a significant interaction between dbh and species, $p<0.0001$ (Figure 2). For the majority of species, there was a linear trend of mean maximum scorch height increasing with increasing mean dbh for the species (Figure 2). On the other hand, sourwood and blackgum (*Nyssa sylvatica* Maarsh.), both very rough-barked species, had high mean maximum scorch heights, 1.03 and 0.77 m respectively, but relatively low mean DBH of 10.3 and 8.3 cm, respectively. Conversely, white oak and northern red oak (*Q. rubra* L.) had high mean DBH (25.8 and 30.3 cm, respectively) but low maximum scorch (0.64 and 0.65 m, respectively).

Maximum scorch height was lower on mesic plots (0.30 ± 0.02 m) compared to xeric (0.88 ± 0.05 m) and intermediate plots (0.69 ± 0.03 m). The effect of landscape position was observable on both species and dbh classes (Figures 3a and b). For all but the two largest DBH classes, there was a trend of increasing scorch height from mesic to xeric within size classes (Figure 3a). Red maple is useful for illustrating the consistency of the landscape effect across species, as it is found across an array of landscape positions (Burns and Honkala, 1990), and occurred fairly evenly across our landscape positions. Red maple showed a clear trend of increasing scorch height along the gradient from mesic to xeric (Figure 3b).

There was considerable variability in fire temperature among plots with significantly higher temperatures recorded at the 0 and 20 cm positions compared to the 40 cm position (Table 1). Temperatures at 0 cm and 20 cm were significant predictors of scorch height ($p=0.015$ and $p<.0001$, respectively). The correlation between scorch height and mean plots temperatures at 0 ($R^2 = 0.33$) and 20 cm ($R^2 = 0.48$) were obtained through a simple linear regression (Figure 4). The interaction between landscape position and temperature at the 20 cm position was also significant, with mesic plots having lower mean maximum temperatures (186.9 ± 80.3°C) than intermediate (288.8 ± 120.8°C) and xeric (305.2 ± 103.8°C) plots.

Fuel accumulation was hypothesized to be a significant predictor of scorch height because of its potential to impact fire behavior and intensity. Scorch height was predicted by both litter amount ($p<0.0001$) and wood presence near the bole ($p<0.002$), with higher scorch heights on trees that had plentiful litter or down wood adjacent to them. Mean forest floor consumption ($p<0.0001$), rather than pre or post burn litter mass, was a consistent predictor of scorch height with higher scorch on plots with more forest floor fuel consumed. An interaction effect of landscape position by forest floor consumption was also a predictor of scorch height ($p=0.0003$). Only 41.7% of the litter layer (Oi) was consumed on mesic plots, compared to 54% on intermediate plots and 73% on xeric plots. The effect of forest floor consumption by mean maximum temperature surpassed at 0 cm was also a significant predictor of bark scorch heights ($p<0.0001$). For every increase of temperature and forest floor consumption, mean scorch height also increased.

Plot steepness, percent slope by class, was also a significant predictor of maximum bark scorch height ($p<0.0001$), with plots on steeper slopes having higher maximum scorch heights. An interaction of slope with fire temperature at 20 cm above the forest floor was also a predictor of scorch height ($p<0.0001$), however the direction of relationship was unclear (Figure 5). Analysis of variance revealed that mean maximum temperature did not vary by slope class ($p= 0.10$).

3.3 Tree survival

The logistic regression analysis of tree survival from 2002 to 2003 showed that survival was influenced by maximum scorch height ($p<0.0001$), defoliation by canopy arthropods ($p= 0.0213$), pre-burn dbh ($p<0.0001$), and species ($p<0.0001$). Sugar maple, flowering dogwood, and blackgum were the tree species that were experienced the highest mortality, while yellow pine, black oak, and scarlet oak had the lowest mortality within 3 months of the fires. Significant defoliation of oak trees by caterpillars occurred on sites during the study period. Five species of oaks were defoliated including white oak, with 42% of the trees affected, black oak (28%), scarlet oak (*Q. coccinea* Muenchh., 15.9%), chestnut oak (*Q. prinus* L., 5%), and northern red oak (4.8%). Of these five oaks, white oaks were the most likely to have died within 3 months of the burn, while black and scarlet oaks were the least likely to succumb. The preferential defoliation of oaks led to a confounding in the logistic regression model of species and defoliation. When species was removed from the model, significance of defoliation increased from $p=0.0213$ to $p=0.0096$, because the significance attributed to species was partially explained by defoliation of white oak leading to higher mortality. There was a negative relationship with pre-burn dbh and maximum scorch height as larger trees tended to have the highest scorch heights, yet it was trees with low scorch and small DBH that died.

There were significant differences in tree mortality between the fire-excluded and burn treatments for the 2 to 4.9 and 5 to 9.9 cm dbh classes (Figure 6). The highest mortality on the burned sites was in trees 2 to 4.9 cm dbh and ranged from 43% on the Chestnut Cliffs site to 72% on Wolfpen. Mortality for the 2 to 4.9 cm size class on fire excluded treatments was considerably lower ranging from 5% on the Buck Creek site to 8% on the Wolfpen. Mortality on the burned sites was also high for 5 to 9.9 cm dbh trees, ranging from 46% on Wolfpen to 17 on Chestnut Cliffs, while mortality on the fire-excluded sites ranged from none on Chestnut Cliffs to 7% on Wolfpen.

4. Discussion

Despite the fact that bark scorch is frequently cited as a measure recorded after prescribed burns and wildfires in coniferous and other forest types (Peterson and Arbaugh, 1986; Uhl and Kauffman, 1990; Regelbrugge and Conard, 1993; Smith and Sutherland, 1999; Bird and Scholes, 2001; Menges and Deyrup, 2001; Barlow et al., 2003), little discussion of its predictive abilities has recently occurred. In this study I was interested in examining scorch height for its ability to predict bole damage, tree mortality, and as a relative measure of fire intensity.

4.1 Scorch height predictors

Both DBH and species strongly influenced bark scorch independently. The interaction of DBH and species was attributed to variability in bark or to the landscape position in which certain species are commonly found. Tree species with strongly fissured, scaly, or flaky bark appeared be more likely to combust and blacken than smooth barked species. Much work has been done to correlate cambium mortality during fire with bark characteristics such as thickness, density, thermal conductivity, and moisture content (Spalt and Reifsnyder, 1962; Fahnestock and Hare, 1964; Hare, 1965a; Hare, 1965b; Gill, 1974; Hengst and Dawson, 1994; Gutsell and Johnson, 1996), yet there is a dearth of information on the relationship between bark characteristics and bark scorch height. When Hengst and Dawson (1994) tested the bark properties and fire resistance of several central hardwood tree species, they found that the bark of species with higher specific gravity values and thinner bark took longer to ignite than the bark of species with lower specific gravities and thicker bark. Hengst and Dawson (1994) also found that species with smooth textured bark maintained lower peak external bark temperatures than species with thicker, fissured bark. The species with the highest peak external bark temperatures were also the species whose bark ignited and produced flames. Uhl and Kauffman (1990) also reported that thin, flaky bark ignited more easily than tight bark. In this study the trees with thick insulating bark, such as black oak and yellow pines, were also the species that had the highest scorch heights (Table 3). Differences in scorch height among species in this study may have been amplified by bark scorch appearing lighter and less extensive on smooth barked trees than on rough barked trees. For example the bark on small red and sugar maple and American beech trees often does not blacken as it does on larger trees but becomes brownish colored, which made measuring scorch heights on these trees more difficult compared to rough-barked species.

Landscape position was an important factor influencing scorch height, most likely due to the influence of landscape position on fire intensity. The interaction effect of maximum temperature at 20 cm above the forest floor by landscape position on bark scorch heights indicated that fires were cooler on mesic plots than on xeric and intermediate plots. Franklin et al. (1997) also reported lower mean temperatures for lower slope positions than at upper slope positions during prescribed fires in oak-maple forests in western Kentucky and Tennessee. Landscape position may affect fire behavior and intensity by modifying soil and forest floor moisture, and through species influences on fuel composition and density (Franklin et al., 1997).

Although not measured, higher forest floor moisture on the mesic plots may have caused less fuel to be available, regardless of accumulation compared to xeric and intermediate plots. A majority of the mesic plots had a strong influence of hillshading, resulting in less solar radiation available to preheat and dry fine fuels. Forest floor consumption, a significant predictor of scorch height, was also a measure of fire severity and contributes to fire intensity (Byram, 1959; Alexander, 1982). The effect of forest floor consumption by landscape position and by the maximum temperature surpassed at the forest floor surface (0 cm) suggests that the lower forest floor consumption and mean fire temperatures in the mesic locations contributed to the lower scorch heights recorded on the mesic plots compared to scorch heights on trees in intermediate and xeric plots.

Three additional variables affecting the height of flames adjacent to tree boles, Slope, wood presence, and litter amount, are three important predictors of maximum scorch height. Slope had a obvious effect on scorch, with scorch height increasing as slope increased, however the significant interaction of slope class and mean maximum temperature at 20 cm was a harder predictor to interpret. In a western Kentucky prescribed burn, fire temperatures were affected by the amount of litter and duff present in spots where the slope was less than 20 degrees, but the steepness of the slope had a greater affect on the fire temperatures than the amount of fuel on slopes greater than 20 degrees (Franklin et al., 1997).

Unfortunately, I was unable to test fire direction as a possible predictor of scorch height in this model as it was not possible to record fire behavior due to the location of the plots within the burn unit and ignition methods. However, the majority of scorch was on the uphill side of trees and Fahnestock and Hare (1964) reported that headfires produced higher flame lengths, or intensity, on the leeward side of trees than flames lengths produced by backing fires. Therefore, fire direction probably would have been a significant predictor of bark scorch heights, particularly on plots with low percent slope.

4.2 Tree mortality

The ability to predict tree mortality after prescribed fires is important to forest managers so they are able to estimate future species composition and stand structure. Tree mortality after the prescribed burns was negatively correlated with scorch heights and with DBH since small trees had the greatest mortality and the lowest scorch heights. Smaller diameter trees had the highest mortality rates due to their thin bark (Harmon, 1984; Van Lear and Waldrop, 1989) and the fact that the flame could easily encompass the entire bole. Van Lear and Waldrop (1989) reported that low-intensity fires generally top-kill most hardwood trees up to 7.5 cm in diameter. Tree mortality on the burn treatments was influenced by species, as Harmon (1984) also found for six species he examined in the Great Smoky Mountains National Park. Harmon (1984) looked at tree survival after low intensity surface fires and found that, after tree diameter, trees with the thinnest bark were most susceptible to mortality following fire. Tree species in this study ranged from very thin-barked, such as red and sugar maple, to thick-barked, such as chestnut oak, black oak, and yellow pine, causing mortality rates to vary by species. The defoliation of certain oak species also influenced their mortality in addition to fire effects.

Trees with higher scorch heights were exposed to greater flames than those with little scorch, leading to higher internal temperatures and a greater chance of cambium death. However, damage to overstory trees may also have been caused by crown scorching (Loomis, 1973), particularly during the two April burns when the trees were more phenologically advanced and susceptible to heat damage. Small trees with low crowns are particularly vulnerable to fire after bud break when leaves are flushing even if flames do not pass directly against their stem. In large trees, mortality may also be attributable to the stress of previous droughts and defoliation events in addition to bark and crown scorch. In coniferous forests, crown scorch has been found to be a more important predictor of postfire mortality than bark scorch (Peterson and Arbaugh, 1986); crown scorch was not measured for this study as it would not have been possible to measure crown scorch on trees that were still dormant. Continued tree measurements should result in a stronger relationship between bark scorch and mortality. I expect that future mortality and wounding will also vary by species, with higher rates of mortality and wounding in the thin barked fire sensitive trees.

4.3 Fire intensity and bark scorch height

Fire temperature, a surrogate for fire intensity, was a significant predictor of scorch height in this study. The significant correlations between plot mean max temp and mean scorch indicate that temperature and scorch data are not completely independent, but possibly both a measure of fire intensity. Cain (1984) found that stem-bark scorch heights on pine trees with an average DBH of 2.5 cm consistently underestimated the intensity values calculated using actual observed flame lengths by half, and concluded that stem-bark char heights may therefore provide a sufficient measure of relative fire intensity where observation of flame heights cannot be made. While scorch has been used as a relative measure of fire intensity in pine stands, correlating fire intensity to bark char or scorch height in a mature hardwood forest is more difficult due to the variety of species and diameters. Perhaps there is potential for a single tree species found across landscape positions in sufficient numbers, such as white oak or red maple, to be used in addition to fire temperatures as a relative measure of fire intensity for large scale prescribed fires where observations of flame length and rate of spread cannot be adequately recorded. Research on a smaller scale where flame lengths can be accurately recorded is needed to calculate the relationships between fire intensity and scorching on hardwood tree species.

5. Conclusions

There has been little previous research on bark scorch for the many species found in hardwood forest. The relationships of maximum scorch height with species, diameter, landscape position, fuel presence, and slope will help forest professionals better understand the factors leading to high bark scorch and subsequent fire scar formation. Future correlations of bark scorch with tree wounding and mortality will compliment Loomis' (1973) work in oak hickory stands.

Table 1: Ambient conditions on day of burn and mean maximum temperature (°C) surpassed at three heights above forest floor (0, 20, and 40 cm) for the three study sites: Buck Creek (BC), Wolfpen (WP), and Chestnut Cliffs (CC). Chestnut Cliffs (south) and Chestnut Cliffs (north) are shown separately because they were burned on two different days. Ranges represent the mean maximum of individual plots within burn unit.

Conditions	**CC south**	**CC north**	**BC**	**WP**
Burn date	3/24/03	3/25/03	4/14/03	4/16/03
Time of ignition	1230	1130	1130	1230
Air temperature (°C)	24	26	21.5	28
Relative humidity (%)	39	31	36	36
Wind direction	W	SW	NW	W
Wind speed (km/hr)	0-9	3-11	0-2	4.8-6.4
10-hour fuel moisture (%)	18	14	15	11
Pyrometer	**CC south** (n=10)	**CC north** (n=8)	**BC** (n=23)	**WP** (n=20)
0 cm mean (°C)	474	533	522	575
Range	(87 – 536)	(374 – 617)	(43 – 644)	(469 – 644)
20 cm mean	233	316	229	313
Range	(115 – 359)	(87 – 536)	(67 – 466)	(150 – 550)
40 cm mean	158	234	165	225
Range	(49 – 269)	(49 – 442)	(63 – 353)	(97 – 370)

Table 2: Significant predictors of maximum bark scorch height on trees >2.5 cm dbh from regression model with class variables.

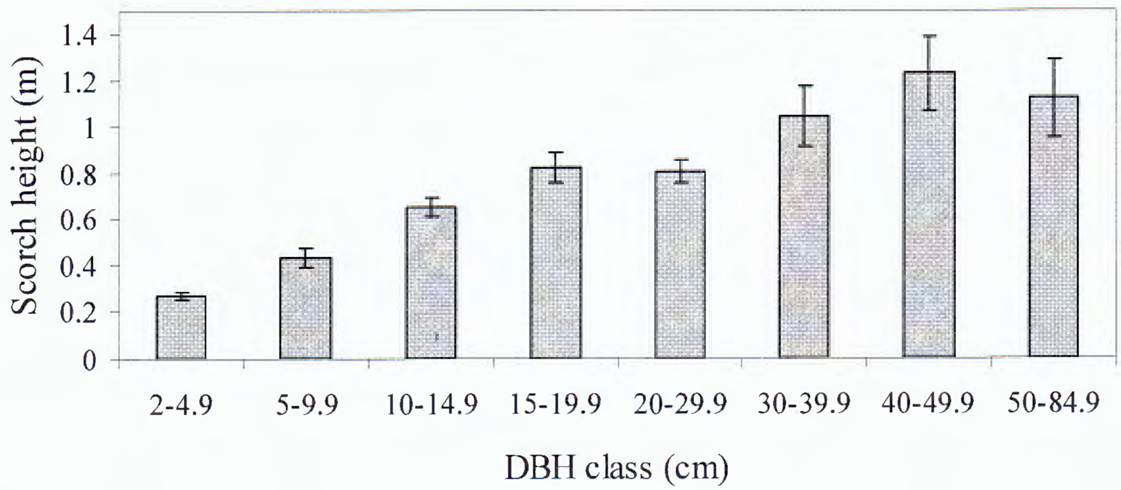
Model Predictor	Data type	Model F-value	Model p-value
DBH class	class	4.8	<0.0001
Species	class	6.0	<0.0001
DBH*SPP	interaction	3.0	<0.0001
Landscape position	class	23.6	<0.0001
Max. temp at 0 cm	continuous	5.9	0.0152
Max. temp at 20 cm	continuous	24.7	<0.0001
LP*Temp at 20 cm	interaction	18.3	<0.0001
Slope	class	10.8	<0.0001
Slope*Temp at 20 cm	interaction	6.9	<0.0001
Forest floor consumption	continuous	25.9	<0.0001
FF consumption*LP	interaction	8.3	0.0003
FF consumption* Temp at 0 cm	interaction	31.9	<0.0001
Wood presence	class	10.2	0.0014
Litter accumulation	class	9.7	<0.0001
Model	-	**23.0**	**<0.0001**

Table 3: Mean maximum scorch height on trees >2.5 cm dbh scorched during prescribed burns by species, with total number of trees on burn treatments, number of trees on burn treatment scorched, and number of trees unscorched.

Species	Total # of trees	Mean scorch height	Standard Error (+/-)	# trees scorched	# of trees w/o scorch
beech	32	0.13	0.03	20	12
blackgum	96	0.77	0.09	87	9
black oak	57	1.20	0.19	51	6
chestnut oak	198	0.99	0.06	165	33
serviceberry	74	0.40	0.05	64	10
dogwood	42	0.41	0.07	34	8
hickory+	118	0.71	0.08	89	29
northern red oak	42	0.65	0.09	38	4
other++	57	0.44	0.05	46	11
red maple	302	0.44	0.03	276	26
sassafras	27	1.06	0.22	25	2
sugar maple	211	0.25	0.02	146	65
scarlet oak	44	0.81	0.11	40	4
sourwood	55	1.03	0.16	51	4
white ash	24	0.94	0.30	21	3
white oak	135	0.64	0.07	87	48
yellow poplar	49	1.12	0.21	40	9
yellow pine+++	10	2.27	0.83	10	0

+'Hickory' includes bitternut, mockernut, pignut, shagbark, and red hickory.
++'Other' includes eastern redbud, birch, slippery elm, black walnut, and white pines.
+++'Yellow pine' includes Virginia pine, pitch pine, and shortleaf pine.

Figure 1: Differences in mean maximum bark scorch heights on all visibly scorched trees by dbh class after prescribed fires in March and April of 2003 on the Daniel Boone National Forest. Standard errors for mean maximum scorch height are reported for each diameter class with error



bars.

Figure 2. Species mean maximum bark scorch heights (gray bars) on all trees visibly scorched with species mean dbh (transparent bars) after prescribed fires in March and April of 2003 on the Daniel Boone National Forest. An interaction effect between species and mean dbh was significant ($p<0.0001$) in predicting mean maximum scorch heights. In general, scorch heights tended to increase as mean dbh increased, however black gum and sourwood had high scorch for their dbh size, while white oak and northern red oak tended to have low scorch for their dbh size. These differences may be the result of differences in bark characteristics or an effect of landscape position. All species groups included in the analysis are not presented in the figure due to space constraints. Species groups excluded include beech, white ash, yellow pine, and other. Standard errors for mean scorch heights are reported for each species group with error bars.

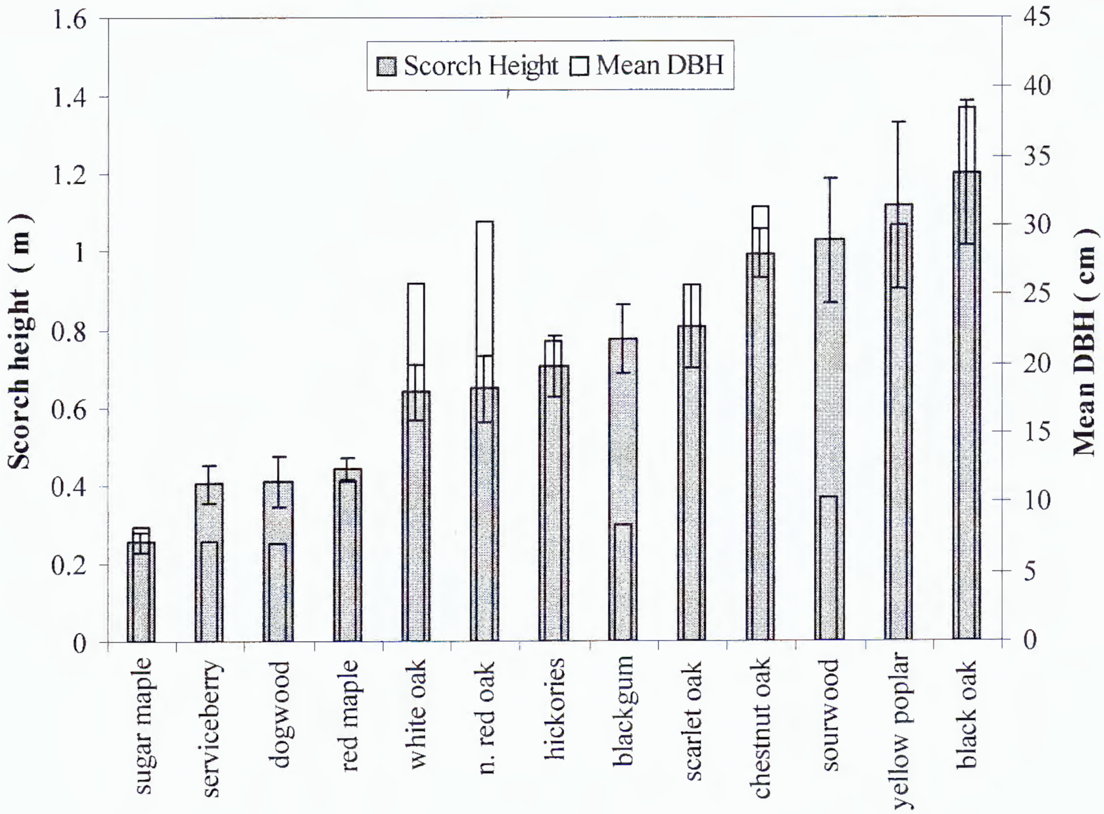
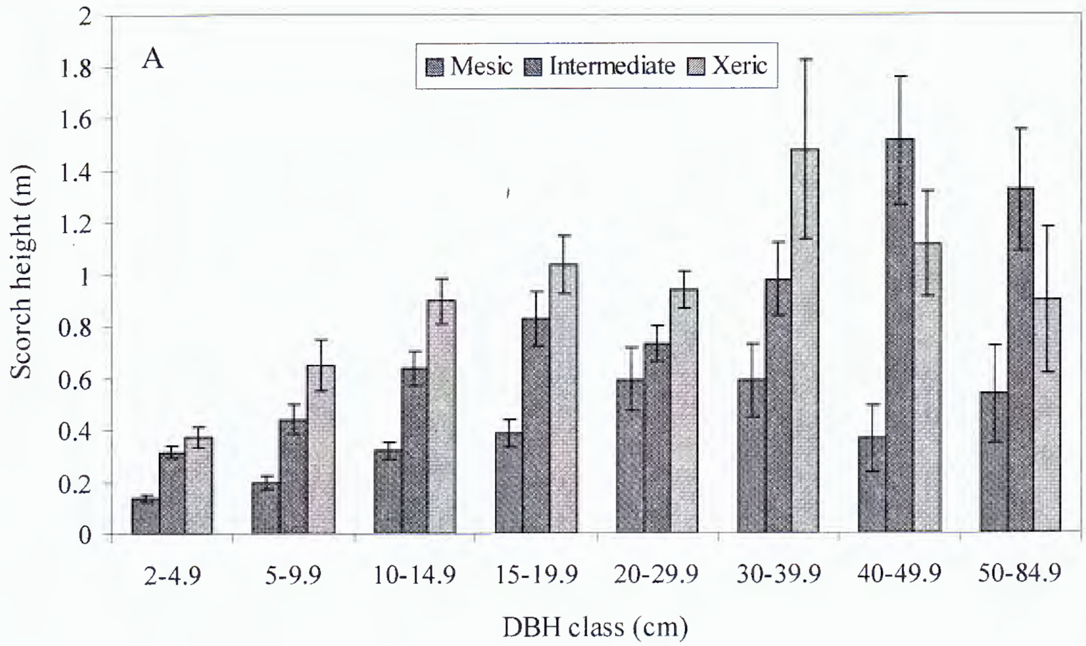


Figure 3: Differences in mean maximum bark scorch heights on all trees visibly scorched after prescribed fires in March and April of 2003 on the Daniel Boone National Forest by A) landscape position and DBH class, and B) landscape position and species. All species groups included in the analysis are not presented in the B due to space constraints. Species groups excluded include beech, white ash, yellow pine, and other. Standard errors for mean scorch heights are reported for each landscape position by dbh class and by species group with error bars.



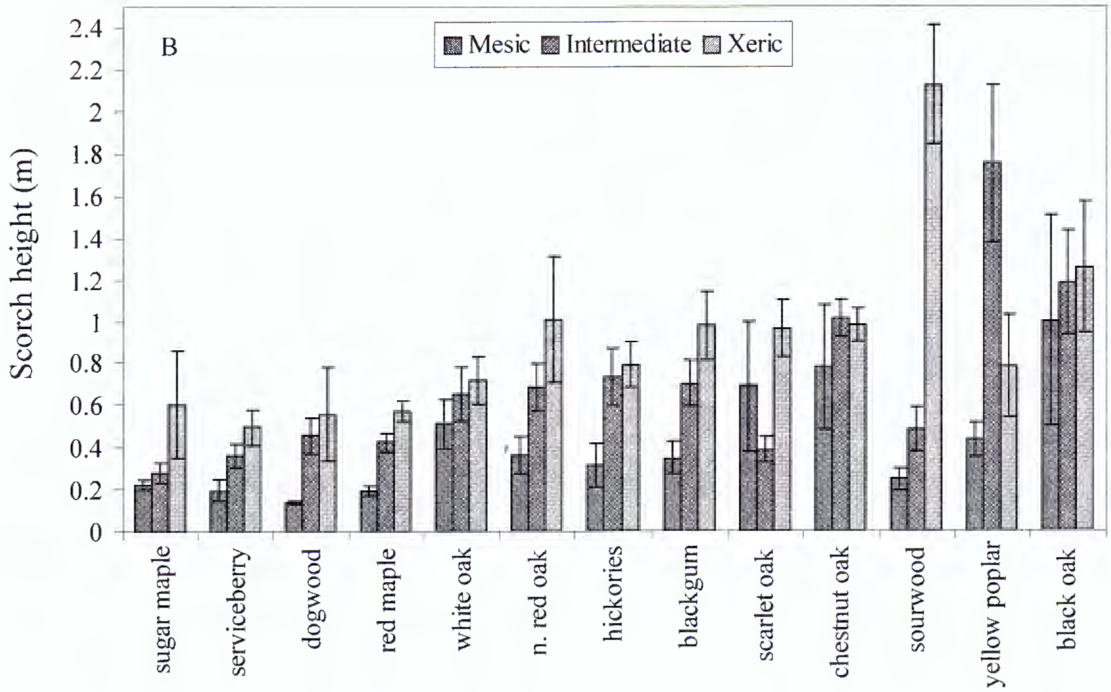
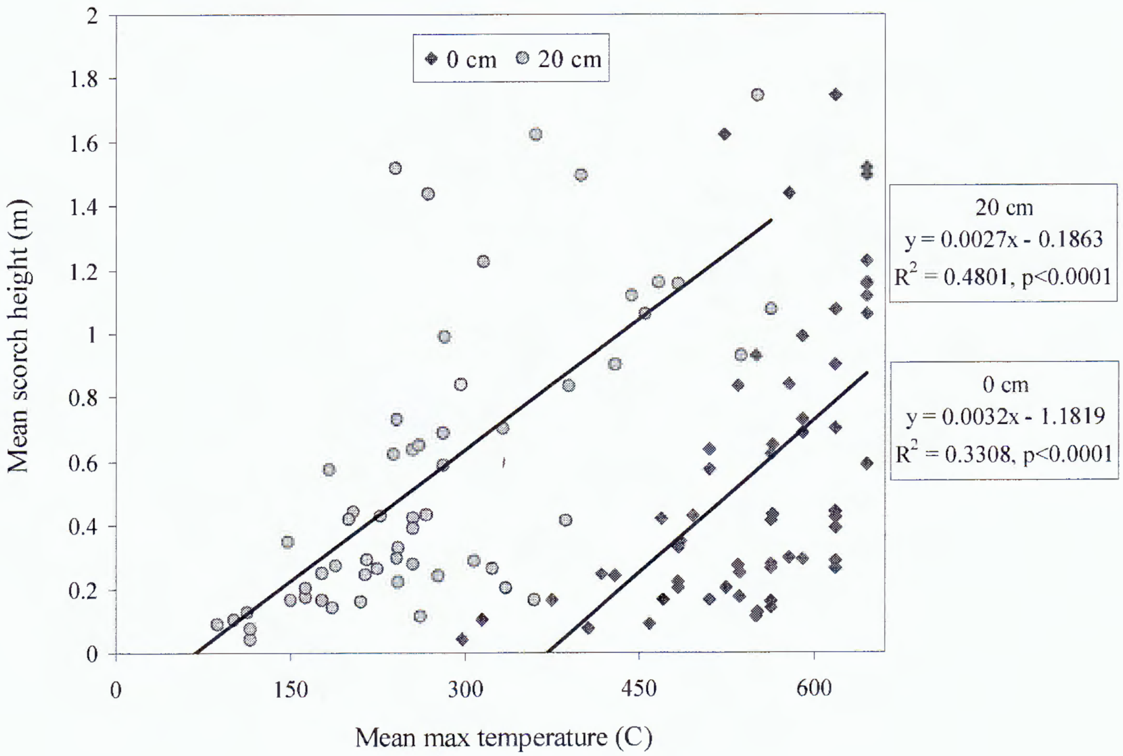


Figure 4. Mean plot (n=61) fire temperatures at 0 and 20 cm positions. Correlations with plot mean maximum bark scorch height are shown.



Mean scorch height (m)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0 cm
20 cm
20 cm
y = 0.0027x - 0.1863
R^2 = 0.4801, p<0.0001
0 cm
y = 0.0032x - 1.1819
R^2 = 0.3308, p<0.0001
0
150
300
450
600
Mean max temperature (C)

Figure 5: Mean maximum temperatures (°C) by plot slope class. The number of plots within each slope class is given above the standard error bar for each mean.

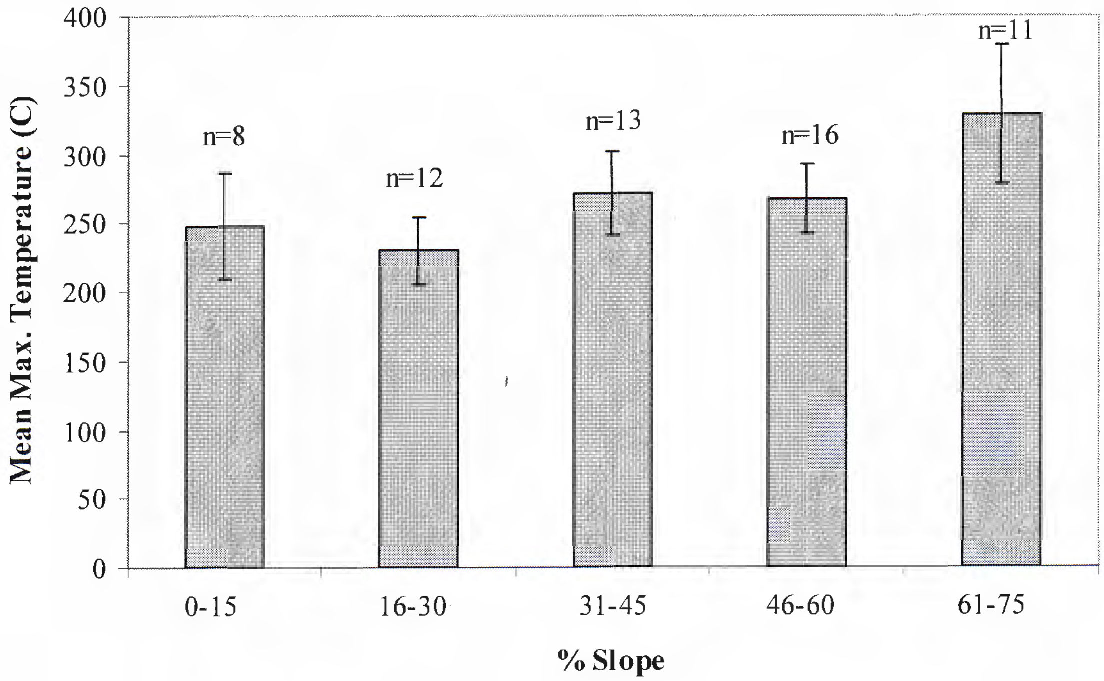
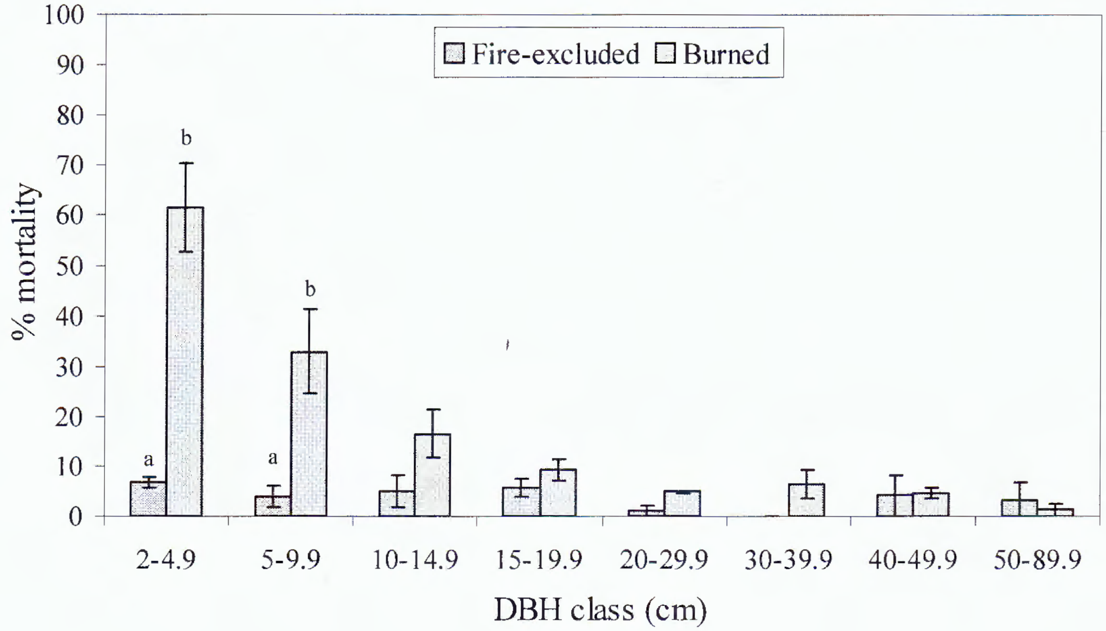


Figure 6: Mean percent mortality and standard error (n=3) of trees in the fire-excluded treatments and burned treatments sorted by DBH class. Lower case letters represent significant differences between fire-excluded and burned treatments within dbh class at $p<0.05$.



APPENDIX 1

Fire intensity background and mean fire temperatures

Fire intensity is defined as "the rate of energy release, or rate of heat release, per unit time per unit length of fire front (Brown and Davis, 1973)." Intensity is often given in kilowatts per meter length of fire front (Barnes et al., 1998) or in Btu per foot per second. Two equations are used to calculate fire intensity, *I*, from flame length. Byram developed the equation: $h = 0.45I^{0.46}$ with *h* representing flame length in feet. The second equation used to calculate fireline intensity from flame length, $I = 5.67\ L_f^{2.17}$ with Lf representing flame length was developed by (Rothermel and Deeming, 1980). However it is difficult to precisely measure the flame length or residence time because of the risks involved in getting close to an actively moving fire, and the smoke produced often obscures visibility. Photographs are not useful for measuring flame length except in areas with a narrow fuel bed or when there is a single line of fire approaching the camera (Rothermel and Deeming, 1980; Simard et al., 1989). For this reason it is difficult to obtain intensity estimates for a large fire based on flame length alone.

Figure 1: Mean mean maximum temperature (°C) surpassed at three heights above forest floor (0, 20, and 40 cm) for the three study sites: Buck Creek (BC), Wolfpen (WP), and Chestnut Cliffs (CC) at the three landscape positions: mesic, intermediate, and xeric. Standard deviations and standard errors are also given.

CM	Site	LP		mean	stddev	Standard error
	i	s		diffic	ult to	preci
		ea		sure th	e flame	lengt
		es		iden	ce tim	e beca
	f		t	h	e	
		i		nvolved	in get	ting c
		o		an acti	vely m	oving
		an		d the s	moke	roduce
	e	n		o	b	
		v		isibili	ty. P	hotogr
		re		not us	eful f	or mea
		f		lame le	ngth e	xcept
r	e	a	s		w	
		na		rrow fu	el bed	or whe
		e		is a si	ngle li	ne of
		pp		roachin	g the c	amera
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		ee		ming, 1	980; S	imard
		,		1989).	For t	his re
		t		is diff	icult	to obt
	n	t	e	n	s	
		ti		mates f	or a l	arge f
		se		d on fl	ame len	gth al
				Figu	re 1:	Mean
m	a	x	i	m	u	
		er		ature (	°C) surpas	sed at
		h		eights	above f	orest
		(0		, 20, a	nd 40 c	m) for
	t	h	r	e	e	
		s		ites:	Buck	reek (
		ol		fpen (W	P), an	d Che
		li		ffs (CC	) at t	he thr
	n	d	s	c	a	
		it		ions: m	esic,	interm
		,		and	xeric.	Stan
		ev		iations	and s	tandar
r	o	r		s		a

APPENDIX 2

Fuel data structure and mass

Notes on Statistical Analysis

Chestnut Cliff fire-excluded plots 138 and 139 were removed from the data set because of labeling problems that occurred during the first year. This left the remaining eight plots in the analysis.

Fuel reduction by site

Analysis of variance was used to examine the difference in preburn and postburn fuel loads to determine if there were significant differences in reduction among study sites (n=3) and treatments (n=2), and to test for a site by treatment interaction.

While the repeated measures split-plot analysis did not detect a significant reduction in the Oea layer (Chapter 2, Figure 6), the ANOVA analysis of the difference in preburn and postburn fuel loads showed that there were significant differences among sites in reduction of the Oea. Plots on the Wolfpen site had the greatest decrease in duff (6.4 Mg/ha, or 31%), followed by Buck Creek with a decrease of 3.8 Mg/ha (17%), while mean duff mass on the Chestnut cliffs burned plots increased by 2.9 Mg/ha (17%).

The ANOVA analysis of the difference in preburn and postburn fuel loads also showed significant differences between sites in the total fuel load were also found, with the Buck Creek and Wolfpen burn treatment having similar reductions, 11.7 Mg/ha (23%) and 11.9 Mg/ha (30%) respectively, while total fuel load did not change on the Chestnut Cliffs burn treatment due to the higher measured duff mass (Appendix 2, Figure 1).

The consumption of duff, Oe and Oa, during fire in eastern white pine stands has been correlated with moisture content (Van Wagner, 1972). Therefore it makes sense that we saw the greatest reduction of duff on the Wolfpen sites when fuel moistures as measured by 10-hour fuel sticks was low, 11%, and hottest fire temperatures and highest range of temperatures occurred (Chapter 2, Table 2).

Paired plot fuel reduction analysis

A paired plot analysis T-test, which did not account for landscape position or site effects, showed a significant decrease of duff on our burn plots of ($p<0.02$ (0.014), n=62). However, the T-test does not take into account effects of landscape position and site on duff fuel reduction, which the repeated measures split-plot analysis did. Consistent with the repeated measures analysis, the paired t-test showed a reduction in leaf litter on the burned plots ($p<0.0001$, n=62) and on the fire-excluded plots ($p=0.0001$, n=29). The t-test also found a reduction in one hour woody fuels ($p=0.03$, n=62) on the burn plots and the increase of 1hr fuels on control plots ($p= 0.009$, n=29).

Fuel depths and heights

The depth of litter and duff were recorded at two locations on each transect before and after the prescribed fires during all three measurement periods. The height of the fuel was also recorded for three 30 cm segment of each transect as well (Brown, 1974). This data has not yet been analyzed and is saved under file names "rawpreburnwinter04 transect data.xls" and "littduffcalfortransects.xls."

Figure 1: Preburn and postburn differences on burn treatments in mean duff fuel load on each of the three study sites: Chestnut Cliffs (CC), Buck Creek (BC), and Wolfpen (WP). Latin letters represent significant differences ($p<0.05$) in duff reduction between sites.

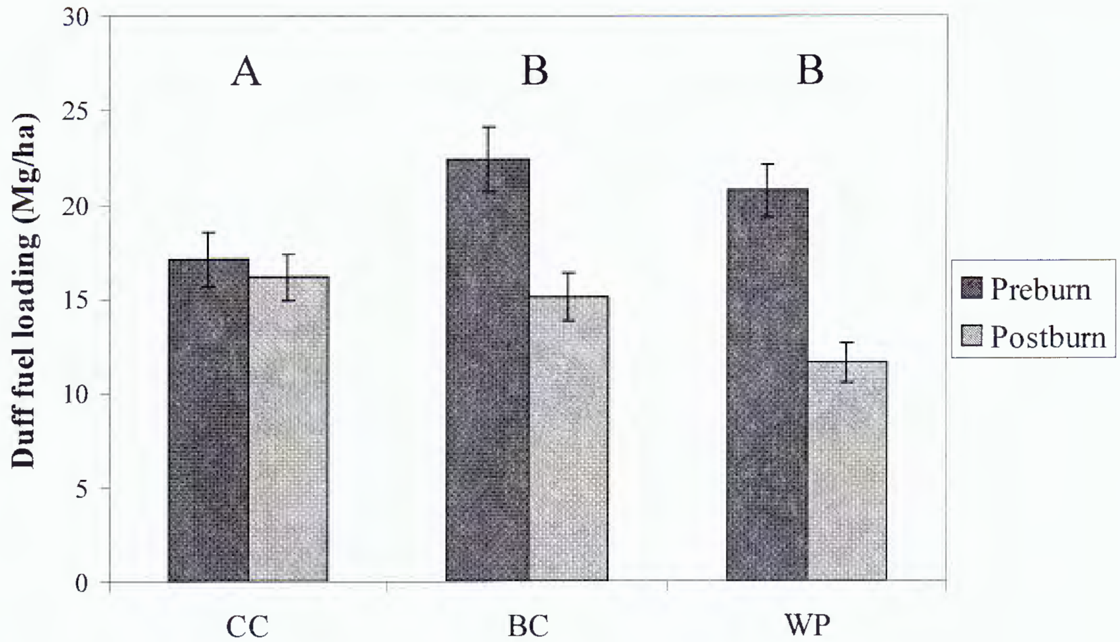

Table 1. Plot Treatment and Landscape Position

Site	Trt	Plot	LP
BC	B	98	M
BC	B	99	M
BC	B	100	I
BC	B	101	X
BC	B	102	M
BC	B	103	X
BC	B	104	X
BC	B	105	I
BC	B	109	I
BC	B	110	I
BC	B	111	I
BC	B	112	I
BC	B	113	I
BC	B	114	X
BC	B	115	I
BC	B	116	I
BC	B	117	X
BC	B	118	M
BC	B	119	M
BC	B	121	X
BC	B	122	I
BC	B	124	I
BC	B	132	X
BC	FE	126	I
BC	FE	127	I
BC	FE	128	M
BC	FE	129	X
BC	FE	130	M
BC	FE	131	M
BC	FE	134	I
BC	FE	135	X
BC	FE	136	I
BC	FE	137	X
CC	B	76	M
CC	B	77	X
CC	B	78	I
CC	B	79	M
CC	B	81	I
CC	B	82	I
CC	B	83	I
CC	B	84	M
CC	B	85	M
CC	B	141	M
CC	B	142	I
CC	B	143	X
CC	B	144	I
CC	B	145	X
CC	B	146	I
CC	B	147	M
CC	B	148	M
CC	B	149	I
CC	B	150	X
CC	FE	80	M
CC	FE	88	I
CC	FE	89	X
CC	FE	90	I
CC	FE	91	I
CC	FE	92	I
CC	FE	94	X
CC	FE	95	M
CC	FE	96	I

Table 1 continued

Site	Trt	Plot	LP
WP	B	2	I
WP	B	5	M
WP	B	6	I

WP	B	10	X
WP	B	11	I
WP	B	12	I
WP	B	14	X
WP	B	15	I
WP	B	16	X
WP	B	20	X
WP	B	21	I
WP	B	22	I
WP	B	23	X
WP	B	24	I
WP	B	25	M
WP	B	26	M
WP	B	27	I
WP	B	28	I
WP	FE	31	M
WP	FE	32	M
WP	FE	33	I
WP	FE	35	X
WP	FE	36	M
WP	FE	37	X
WP	FE	38	M
WP	FE	39	I
WP	FE	40	M
WP	FE	42	I

Table 2. Plot fuel means with 'Lvs' signifying the mass of leaves only and 'WBS' signifying the mass of wood, bark, and seeds from the forest floor block litter layer.

Site	Plot	Time	Lvs	Duff	WBS	1-hr	10-hr	100-hr	1000-hr	Total
BC	98	Preburn	2.97	18.83	0.66	0.83	2.78	4.89	23.04	53.34
BC	98	Postburn	0.06	19.90	1.60	0.39	2.40	4.89	12.36	39.99
BC	98	Post leaf fall	2.20	9.09	0.48	0.39	3.96	3.20	12.35	31.19
BC	99	Preburn	2.84	52.08	0.74	1.96	11.23	13.85	16.26	98.21
BC	99	Postburn	1.55	30.11	2.11	1.17	7.43	19.53	18.23	78.02
BC	99	Post leaf fall	2.23	14.87	1.21	2.05	11.57	21.62	33.86	86.19
BC	100	Preburn	2.64	15.07	1.58	0.47	4.90	2.99	3.95	30.02
BC	100	Postburn	0.18	7.73	2.73	0.37	2.27	1.50	4.22	16.26
BC	100	Post leaf fall	2.70	6.96	1.40	0.20	1.13	4.50	10.72	26.22
BC	101	Preburn	3.19	22.30	1.09	0.38	3.52	6.58	3.86	39.83
BC	101	Postburn	0.09	26.03	1.03	0.67	2.72	1.69	5.37	36.57
BC	101	Post leaf fall	1.22	19.63	0.51	0.70	1.92	0.00	7.85	31.32
BC	102	Preburn	2.51	14.90	0.45	0.32	1.54	1.50	58.16	78.93
BC	102	Postburn	0.70	22.59	1.89	0.84	3.09	6.35	68.43	101.99
BC	102	Post leaf fall	2.33	9.14	1.83	0.77	3.13	9.34	98.87	123.58
BC	103	Preburn	2.57	25.68	0.96	0.27	0.78	1.50	1.73	32.53
BC	103	Postburn	0.11	35.36	1.45	0.56	1.57	2.99	3.26	43.85
BC	103	Post leaf fall	1.48	21.63	0.50	0.59	1.50	1.50	12.32	39.01
BC	104	Preburn	3.08	22.93	0.96	0.24	0.75	5.99	2.55	35.53
BC	104	Postburn	0.17	24.98	1.93	0.27	0.75	5.99	2.79	34.95
BC	104	Post leaf fall	2.76	15.79	1.76	0.40	1.50	2.99	2.60	26.05
BC	105	Preburn	4.36	22.15	0.73	0.41	1.89	1.53	18.40	48.74
BC	105	Postburn	0.37	16.38	2.37	0.37	1.13	1.50	24.20	43.96
BC	105	Post leaf fall	2.94	19.81	2.66	0.24	1.51	2.99	4.99	32.47
BC	109	Preburn	2.85	27.09	0.47	0.41	1.88	4.51	4.18	40.92
BC	109	Postburn	0.21	10.50	1.84	0.27	1.50	4.49	4.49	21.45
BC	109	Post leaf fall	3.10	9.27	2.89	0.34	2.26	4.49	6.17	25.62
BC	110	Preburn	2.19	15.91	1.03	0.58	4.95	18.06	2.95	44.65
BC	110	Postburn	0.07	15.11	1.27	0.31	2.67	9.09	3.02	30.26
BC	110	Post leaf fall	2.34	3.19	2.42	0.44	4.19	7.55	4.49	22.21
BC	111	Preburn	4.23	25.06	2.89	1.89	7.43	10.16	20.06	68.82
BC	111	Postburn	0.24	27.60	1.37	0.44	2.68	4.89	12.13	47.97
BC	111	Post leaf fall	3.38	4.06	2.61	0.83	9.49	18.78	15.16	51.70
BC	112	Preburn	2.23	22.46	1.30	0.76	0.40	3.18	0.67	29.69
BC	112	Postburn	0.04	9.28	2.66	0.96	1.15	1.59	2.43	15.44
BC	112	Post leaf fall	3.00	14.26	2.71	0.49	1.93	3.18	3.19	26.05
BC	113	Preburn	4.40	21.83	2.20	1.63	10.57	11.96	4.38	54.78
BC	113	Postburn	0.23	23.55	1.98	0.61	3.43	4.59	0.00	32.41
BC	113	Post leaf fall	2.41	8.79	1.96	0.58	6.43	4.59	0.00	22.80

Table 2 continued

Site	Plot	Time	Lvs	Duff	WBS	1-hr	10-hr	100-hr	1000-hr	Total
BC	114	Preburn	3.82	31.14	1.13	0.94	5.24	7.48	12.32	60.93
BC	114	Postburn	0.09	12.19	0.49	0.27	3.37	7.48	8.53	31.92
BC	114	Post leaf fall	2.43	11.79	1.46	0.20	3.74	8.97	10.25	37.38

BC	116	Post leaf fall	3.26	5.51	2.79	0.50	5.24	10.47	9.80	34.78
BC	117	Preburn	3.50	24.35	5.34	0.70	4.03	2.99	0.90	36.48
BC	117	Postburn	0.11	14.47	1.65	0.35	0.81	2.99	0.98	19.71
BC	117	Post leaf fall	0.65	6.79	2.89	0.93	3.17	2.99	1.44	15.96
BC	118	Preburn	3.11	13.66	1.00	0.21	2.32	8.05	13.14	40.49
BC	118	Postburn	0.08	9.26	0.71	0.26	2.46	5.98	12.26	30.31
BC	118	Post leaf fall	1.83	16.73	2.51	0.55	4.48	6.27	19.03	48.88
BC	119	Preburn	4.47	16.43	1.91	0.49	1.13	1.50	84.22	108.24
BC	119	Postburn	0.30	13.23	0.63	0.48	2.12	0.00	18.11	34.23
BC	119	Post leaf fall	2.73	14.16	3.26	0.78	6.07	3.65	43.71	71.11
BC	121	Preburn	3.51	14.46	1.32	0.31	3.88	4.77	19.50	46.43
BC	121	Postburn	0.08	16.19	0.76	0.59	0.82	1.64	29.62	48.94
BC	121	Post leaf fall	1.51	4.47	0.71	0.51	1.16	0.00	4.51	12.16
BC	122	Preburn	2.99	25.31	1.57	0.90	3.20	1.66	32.00	66.07
BC	122	Postburn	0.19	24.83	0.70	0.14	1.16	1.50	10.01	37.84
BC	122	Post leaf fall	1.68	11.04	0.90	0.32	3.20	4.82	14.39	35.46
BC	124	Preburn	2.14	14.02	1.57	0.43	3.55	3.13	6.81	30.07
BC	124	Postburn	0.34	13.98	1.77	0.59	1.91	7.48	4.61	28.90
BC	124	Post leaf fall	1.92	5.78	2.57	0.45	2.28	10.61	4.92	25.96
BC	132	Preburn	3.31	28.75	1.34	0.53	2.37	4.68	2.62	42.26
BC	132	Postburn	0.10	23.34	0.73	0.63	1.59	0.00	24.64	50.30
BC	132	Post leaf fall	3.68	12.49	4.18	0.56	2.34	1.50	73.58	94.15
BC	126	Preburn	2.79	9.59	0.67	0.44	1.89	6.04	6.48	27.23
BC	126	Postburn	2.14	9.82	1.21	0.51	2.66	4.54	1.71	21.38
BC	126	Post leaf fall	3.03	3.90	1.84	0.31	3.04	3.03	3.02	16.33
BC	127	Preburn	2.53	21.28	0.60	0.32	3.23	4.64	1.70	33.69
BC	127	Postburn	1.83	15.13	2.04	0.64	3.48	3.30	7.77	32.16
BC	127	Post leaf fall	4.45	4.96	3.49	0.52	3.45	3.30	10.96	27.64
BC	128	Preburn	2.21	15.45	1.59	0.47	4.14	3.04	7.90	33.21
BC	128	Postburn	1.87	13.57	1.19	0.64	3.39	8.99	2.36	30.83
BC	128	Post leaf fall	2.85	8.15	3.69	0.44	5.65	10.49	3.76	31.35

Table 2 continued

Site	Plot	Time	Lvs	Duff	WBS	1-hr	10-hr	100-hr	1000-hr	Total
BC	129	Preburn	2.47	22.41	0.99	0.73	5.01	9.25	3.77	43.65
BC	129	Postburn	1.85	27.61	2.50	1.11	4.31	7.74	1.32	43.95
BC	129	Post leaf fall	3.96	10.68	3.97	0.62	4.79	9.15	2.04	31.24
BC	130	Preburn	2.82	15.71	0.61	0.71	4.70	7.76	1.19	32.89
BC	130	Postburn	1.82	14.48	1.50	0.36	2.05	1.64	22.72	43.05
BC	130	Post leaf fall	4.90	11.33	1.78	0.35	2.87	1.64	27.59	48.66
BC	131	Preburn	2.77	20.05	1.18	0.37	4.14	1.50	19.13	47.97
BC	131	Postburn	2.98	25.28	1.56	0.71	2.25	6.00	2.01	39.22
BC	131	Post leaf fall	6.33	21.11	4.86	0.84	2.63	4.49	0.00	35.40
BC	134	Preburn	1.86	28.63	3.76	0.47	2.99	2.99	21.51	58.46
BC	134	Postburn	4.40	18.89	2.88	0.64	4.12	4.49	15.93	48.46
BC	134	Post leaf fall	5.24	12.25	2.08	0.24	5.24	2.99	43.77	69.72
BC	135	Preburn	3.02	23.41	2.06	0.45	2.73	3.10	31.30	64.00
BC	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

BC	136	Post leaf fall	3.57	8.09	1.28	0.64	1.54	6.32	56.76	76.91
BC	137	Preburn	4.28	26.62	0.80	0.65	3.04	6.17	14.71	55.47
BC	137	Postburn	3.48	14.95	0.99	0.73	1.97	3.09	1.32	25.54
BC	137	Post leaf fall	4.88	14.37	2.92	1.11	1.97	7.86	1.58	31.78
CC	76	Preburn	2.99	18.70	1.35	0.51	0.38	0.00	21.05	43.62
CC	76	Postburn	1.28	24.10	1.89	0.47	1.88	0.00	21.77	49.50
CC	76	Post leaf fall	2.53	12.30	1.63	0.41	1.51	0.00	0.00	16.75
CC	77	Preburn	4.74	31.91	1.50	1.70	7.64	6.22	16.45	68.66
CC	77	Postburn	0.01	29.58	0.52	0.14	1.90	7.72	6.62	45.97
CC	77	Post leaf fall	4.62	14.82	0.56	0.55	2.34	12.20	7.30	41.83
CC	78	Preburn	2.56	6.03	3.51	0.38	1.12	2.99	18.27	31.36
CC	78	Postburn	0.29	9.74	1.41	0.25	1.60	0.00	16.22	28.10
CC	78	Post leaf fall	2.45	6.88	0.36	1.35	4.09	5.08	14.30	34.15
CC	79	Preburn	2.48	25.27	0.78	0.41	0.77	1.50	0.00	30.42
CC	79	Postburn	0.30	27.84	1.36	0.35	1.94	4.49	0.00	34.92
CC	79	Post leaf fall	3.43	21.68	1.53	0.52	2.34	2.99	0.72	31.68
CC	81	Preburn	3.12	13.99	0.32	0.34	1.51	0.00	31.55	50.50
CC	81	Postburn	0.29	13.96	2.02	0.71	1.51	0.00	24.23	40.70
CC	81	Post leaf fall	4.44	6.42	0.54	0.51	3.39	1.50	45.85	62.11
CC	82	Preburn	3.33	27.54	0.60	0.42	2.71	4.59	7.54	46.13
CC	82	Postburn	0.62	14.18	1.96	0.31	2.71	4.59	14.27	36.68
CC	82	Post leaf fall	2.47	11.09	3.30	0.38	3.47	1.55	14.32	33.28

Table 2 continued

Site	Plot	Time	Lvs	Duff	WBS	1-hr	10-hr	100-hr	1000-hr	Total
CC	83	Preburn	1.79	11.27	2.89	0.52	2.71	1.56	1.63	19.47
CC	83	Postburn	0.29	9.81	0.58	0.55	1.51	3.13	1.74	17.04
CC	83	Post leaf fall	1.44	6.12	1.09	0.66	3.47	3.13	3.88	18.70
CC	84	Preburn	2.90	17.03	0.70	0.34	1.88	10.51	1.21	33.87
CC	84	Postburn	0.16	24.99	0.42	0.24	3.01	13.53	0.00	41.92
CC	84	Post leaf fall	2.55	10.80	0.63	0.47	4.12	13.53	0.00	31.47
CC	85	Preburn	2.56	17.77	0.25	0.27	2.30	3.07	13.80	39.78
CC	85	Postburn	1.46	16.94	2.75	1.24	6.05	7.55	16.37	49.61
CC	85	Post leaf fall	2.55	8.95	1.40	0.62	7.58	9.05	18.62	47.37
CC	141	Preburn	4.02	13.98	1.49	0.45	2.36	1.50	0.93	23.24
CC	141	Postburn	2.59	24.08	1.13	0.34	3.46	6.10	0.00	36.56
CC	141	Post leaf fall	4.33	8.17	1.69	0.45	4.23	1.50	2.06	20.73
CC	142	Preburn	3.74	13.32	0.94	0.27	3.74	2.99	0.00	24.06
CC	142	Postburn	1.24	16.30	2.12	0.47	0.75	1.50	0.00	20.26
CC	142	Post leaf fall	3.70	5.23	1.76	0.47	3.37	2.99	2.06	17.82
CC	143	Preburn	2.81	20.56	0.81	0.65	1.90	0.00	0.00	25.92
CC	143	Postburn	0.20	19.68	1.49	0.58	3.03	1.50	0.00	24.98
CC	143	Post leaf fall	4.66	20.86	3.76	0.65	1.51	0.00	2.30	29.98
CC	144	Preburn	2.84	18.51	2.10	0.57	6.51	0.00	0.00	28.42
CC	144	Postburn	0.20	14.95	0.54	0.49	1.96	7.83	4.53	29.96
CC	144	Post leaf fall	3.29	4.80	1.70	0.38	3.11	4.60	13.80	29.98
CC	145	Preburn	4.08	16.78	3.66	0.69	3.07	6.17	3.53	34.31
CC	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

CC	146	Post leaf fall	3.12	2.99	2.12	0.61	2.25	4.49	2.63	16.09
CC	147	Preburn	2.79	13.19	0.67	0.31	0.75	4.53	1.28	22.84
CC	147	Postburn	0.61	32.04	0.90	0.38	2.67	0.00	13.99	49.68
CC	147	Post leaf fall	5.59	5.70	2.46	0.61	2.28	1.50	23.33	39.01
CC	148	Preburn	3.93	16.14	2.14	0.72	2.33	3.16	16.36	42.66
CC	148	Postburn	1.64	25.36	0.21	0.62	2.69	7.75	8.44	46.49
CC	148	Post leaf fall	5.15	15.07	3.23	0.45	1.52	6.25	10.84	39.28
CC	149	Preburn	1.70	9.75	1.56	0.78	3.00	7.50	9.58	32.31
CC	149	Postburn	0.36	11.24	1.40	0.27	3.37	2.99	3.88	22.11
CC	149	Post leaf fall	0.99	6.44	4.67	0.64	4.88	3.00	4.47	20.42
CC	150	Preburn	3.08	19.19	1.45	0.34	4.13	4.51	1.09	32.33
CC	150	Postburn	0.86	20.35	2.66	0.20	1.12	1.50	5.04	29.07
CC	150	Post leaf fall	2.51	14.59	1.63	0.61	3.76	3.04	8.45	32.95

Table 2 continued

Site	Plot	Time	Lvs	Duff	WBS	1-hr	10-hr	100-hr	1000-hr	Total
CC	80	Preburn	3.00	21.41	0.77	0.27	0.78	0.00	5.07	30.54
CC	80	Postburn	0.30	27.84	1.36	0.79	1.53	0.00	3.61	34.07
CC	80	Post leaf fall	2.63	9.65	1.04	0.48	1.53	0.00	4.37	18.66
CC	88	Preburn	3.19	14.14	1.11	1.04	3.75	6.00	6.97	35.09
CC	88	Postburn	3.71	16.56	1.25	0.84	4.87	4.50	6.15	36.63
CC	88	Post leaf fall	5.22	16.77	0.56	0.34	3.37	3.00	10.13	38.82
CC	89	Preburn	1.58	23.05	1.14	0.66	0.78	1.56	5.69	33.33
CC	89	Postburn	0.79	14.41	1.69	0.70	1.16	3.13	1.63	21.81
CC	89	Post leaf fall	1.80	11.45	1.40	0.73	0.00	3.13	4.63	21.74
CC	90	Preburn	2.44	11.35	1.24	0.44	1.50	1.50	1.09	18.31
CC	90	Postburn	2.34	11.04	2.97	0.51	1.50	1.50	1.78	18.67
CC	90	Post leaf fall	3.75	11.86	0.62	0.38	1.87	0.00	0.00	17.85
CC	91	Preburn	4.17	12.57	1.42	0.86	3.80	2.99	0.00	24.39
CC	91	Postburn	2.24	15.77	2.33	1.04	2.27	2.99	0.00	24.32
CC	91	Post leaf fall	3.26	6.14	3.13	0.49	3.53	4.59	0.00	18.02
CC	92	Preburn	2.58	16.80	2.25	1.23	2.65	1.50	10.72	35.48
CC	92	Postburn	1.29	15.51	1.38	1.14	1.90	4.49	0.67	25.00
CC	92	Post leaf fall	3.53	14.92	1.43	0.66	3.43	2.99	2.06	27.58
CC	94	Preburn	3.96	16.19	1.74	1.21	1.87	4.49	0.73	28.44
CC	94	Postburn	2.14	25.73	5.39	0.98	3.37	2.99	26.91	62.11
CC	94	Post leaf fall	3.48	17.37	2.28	0.57	4.49	2.99	33.96	62.87
CC	95	Preburn	4.03	21.96	1.21	0.41	1.93	7.71	18.40	54.44
CC	95	Postburn	3.76	30.11	1.90	0.62	1.16	6.13	14.94	56.72
CC	95	Post leaf fall	3.28	23.61	0.91	0.48	2.74	4.56	33.40	68.06
CC	96	Preburn	3.71	14.33	3.55	0.69	1.56	0.00	10.12	30.42
CC	96	Postburn	1.68	15.73	3.18	0.94	1.94	0.00	0.00	20.29
CC	96	Post leaf fall	2.79	15.64	2.84	0.14	2.34	3.25	19.92	44.09
WP	2	Preburn	3.58	26.97	2.19	0.42	1.65	0.00	4.98	37.60
WP	2	Postburn	0.08	15.55	1.39	0.48	1.20	0.00	0.71	18.03
WP	2	Post leaf fall	2.41	16.32	3.68	0.90	3.60	0.00	33.30	56.53
WP	5	Preburn	3.19	15.77	2.83	0.34	1.51	6.06	14.36	41.23
WP	5	Postburn	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

WP	6	Post leaf fall	2.79	3.48	0.87	0.41	1.21	2.99	1.57	12.46
WP	7	Preburn	4.13	23.25	1.09	0.28	0.38	9.02	18.85	55.90
WP	7	Postburn	0.05	7.64	1.83	0.38	1.58	9.02	19.90	38.57
WP	7	Post leaf fall	2.53	8.08	1.24	0.35	2.16	10.52	29.68	53.32

Table 2 continued

Site	Plot	Time	Lvs	Duff	WBS	1-hr	10-hr	100-hr	1000-hr	Total
WP	9	Preburn	1.99	22.25	2.39	0.44	1.89	6.06	3.80	36.44
WP	9	Postburn	0.10	14.08	0.87	0.37	0.38	3.03	2.97	20.93
WP	9	Post leaf fall	1.35	4.35	0.40	0.95	2.27	1.50	4.38	14.79
WP	10	Preburn	4.94	21.59	1.38	0.62	0.84	4.84	1.63	34.46
WP	10	Postburn	0.09	15.65	0.40	0.31	0.37	1.85	1.70	19.97
WP	10	Post leaf fall	1.06	10.85	0.80	0.40	3.46	3.70	1.52	20.99
WP	11	Preburn	3.45	27.75	3.71	0.61	3.21	4.91	7.41	47.35
WP	11	Postburn	0.05	18.05	2.76	0.17	0.00	3.42	6.90	28.59
WP	11	Post leaf fall	1.53	8.12	3.13	0.25	0.00	3.42	23.78	37.10
WP	12	Preburn	4.34	17.94	1.61	0.31	1.97	1.62	5.39	31.57
WP	12	Postburn	0.12	12.66	1.05	0.49	2.68	0.00	4.08	20.03
WP	12	Post leaf fall	2.69	11.52	2.32	0.32	3.43	3.12	7.18	28.26
WP	14	Preburn	1.96	18.05	0.93	0.50	0.75	1.50	0.64	23.40
WP	14	Postburn	0.16	25.40	1.08	0.34	0.75	2.99	0.63	30.26
WP	14	Post leaf fall	2.57	10.04	4.70	0.77	0.75	2.99	5.90	23.02
WP	15	Preburn	3.31	27.62	1.70	0.59	1.93	5.98	3.06	42.49
WP	15	Postburn	0.13	17.89	3.00	0.92	9.22	13.35	2.67	44.19
WP	15	Post leaf fall	2.01	13.25	3.00	0.90	6.74	22.55	1.66	47.12
WP	16	Preburn	3.17	21.49	1.20	0.81	2.33	3.15	2.90	33.86
WP	16	Postburn	0.32	20.88	0.59	0.35	0.79	0.00	1.52	23.86
WP	16	Post leaf fall	0.76	4.55	2.09	1.22	5.45	1.50	1.45	14.94
WP	20	Preburn	3.53	23.40	0.90	0.95	3.02	7.50	2.05	40.45
WP	20	Postburn	0.19	22.83	0.92	0.17	0.75	2.99	3.72	30.64
WP	20	Post leaf fall	4.00	18.44	1.10	0.47	2.62	1.50	2.89	29.91
WP	21	Preburn	3.83	21.71	2.49	0.87	1.53	3.11	2.55	33.58
WP	21	Postburn	0.35	20.24	2.31	0.31	2.27	1.50	0.68	25.34
WP	21	Post leaf fall	3.07	7.32	6.12	0.78	1.50	3.11	2.87	18.65
WP	22	Preburn	2.36	25.59	1.09	1.47	4.16	9.68	4.95	48.21
WP	22	Postburn	0.17	17.68	0.84	0.80	2.81	0.00	3.58	25.03
WP	22	Post leaf fall	2.36	4.40	2.08	0.57	3.58	1.69	3.90	16.50
WP	23	Preburn	3.62	34.77	5.17	0.54	3.67	1.69	3.92	48.21
WP	23	Postburn	0.05	9.96	0.99	0.14	0.37	8.07	9.15	27.75
WP	23	Post leaf fall	1.51	9.43	2.08	0.22	1.60	6.38	10.45	29.58
WP	24	Preburn	3.43	9.08	1.96	0.38	1.92	18.42	13.82	47.06
WP	24	Postburn	1.25	12.63	2.50	0.63	0.37	0.00	1.40	16.28
WP	24	Post leaf fall	3.19	1.70	3.06	0.48	1.57	0.00	3.11	10.05
WP	25	Preburn	4.05	12.07	3.19	0.58	2.64	4.53	12.54	36.42
WP	25	Postburn	0.36	7.65	3.81	0.51	2.65	6.03	7.64	24.83
WP	25	Post leaf fall	4.60	3.37	4.43	0.30	1.89	6.03	13.35	29.55

Table 2 continued

Site	Plot	Time	Lvs	Duff	WBS	1-hr	10-hr	100-hr	1000-hr	Total
WP	26	Preburn	2.35	22.64	0.46	0.35	1.55	1.50	3.21	31.60
WP	26	Postburn	0.55	13.88	1.49	0.62	1.17	1.59	4.80	22.61
WP	26	Post leaf fall	4.16	5.01	1.99	0.72	3.04	1.59	10.38	24.91
WP	27	Preburn	2.48	17.35	0.72	0.41	2.27	12.01	3.43	37.95
WP	27	Postburn	0.72	8.35	5.78	0.91	3.38	12.01	20.50	45.87
WP	27	Post leaf fall	4.91	6.46	3.84	0.92	6.03	16.49	51.09	85.90
WP	28	Preburn	3.26	13.19	0.02	0.34	1.90	16.71	3.88	39.28
WP	28	Postburn	0.46	6.81	2.39	0.34	1.90	10.57	3.29	23.37
WP	28	Post leaf fall	4.19	2.24	3.27	0.24	1.52	15.11	4.12	27.42
WP	31	Preburn	3.00	19.02	2.06	0.44	3.38	3.00	1.75	30.59
WP	31	Postburn	1.71	18.17	0.89	0.51	0.75	3.00	3.82	27.95
WP	31	Post leaf fall	2.77	13.67	2.05	0.47	2.26	4.49	3.28	26.94
WP	32	Preburn	3.38	18.89	0.30	0.32	1.18	4.60	65.82	94.19
WP	32	Postburn	1.98	23.38	0.97	0.29	1.18	4.60	46.57	78.01
WP	32	Post leaf fall	3.72	9.19	1.34	0.35	1.96	4.60	80.29	100.11
WP	33	Preburn	3.96	9.89	1.76	0.44	0.39	3.08	6.23	23.99
WP	33	Postburn	1.05	11.12	1.52	0.28	0.76	3.08	9.61	25.90
WP	33	Post leaf fall	3.41	7.32	1.15	0.58	1.51	4.58	8.12	25.51
WP	35	Preburn	2.50	26.22	1.99	0.47	2.26	3.03	1.78	36.26
WP	35	Postburn	1.03	13.42	1.63	0.44	2.25	1.51	4.29	22.95
WP	35	Post leaf fall	2.63	10.68	0.60	0.44	3.01	1.51	3.07	21.34
WP	36	Preburn	2.82	18.12	3.10	0.27	2.71	6.05	12.85	42.82
WP	36	Postburn	1.15	15.76	0.72	0.31	3.06	3.06	22.21	45.55
WP	36	Post leaf fall	3.81	9.58	2.53	0.92	3.05	4.55	19.13	41.04
WP	37	Preburn	3.23	16.87	0.95	0.40	1.12	0.00	0.73	22.36
WP	37	Postburn	2.03	20.61	1.92	0.67	2.62	1.50	3.22	30.65
WP	37	Post leaf fall	3.62	15.14	1.79	0.47	4.49	1.50	4.50	29.72
WP	38	Preburn	2.85	14.98	1.25	0.43	1.61	1.65	0.88	22.40
WP	38	Postburn	1.95	10.23	0.77	0.49	2.85	1.65	0.00	17.18
WP	38	Post leaf fall	2.93	8.17	0.46	0.46	2.28	1.65	1.25	16.74
WP	39	Preburn	3.31	16.35	1.62	0.36	0.78	1.61	1.39	23.80
WP	39	Postburn	2.28	25.10	1.02	0.42	1.59	1.61	1.52	32.52
WP	39	Post leaf fall	2.65	18.09	0.92	0.61	1.96	1.61	1.50	26.41
WP	40	Preburn	2.23	11.50	4.38	0.53	2.35	3.13	0.00	19.75
WP	40	Postburn	1.65	22.07	1.19	0.51	2.35	6.41	0.00	33.00
WP	40	Post leaf fall	4.16	10.50	2.00	0.60	1.98	4.91	2.88	25.02
WP	42	Preburn	2.33	13.15	4.05	0.17	1.92	19.85	4.19	41.60
WP	42	Postburn	0.56	12.39	0.76	0.34	1.53	4.49	6.25	25.56
WP	42	Post leaf fall	2.76	9.13	0.52	0.48	2.28	2.99	7.20	24.84

APPENDIX 3

Bark scorch and tree mortality

Notes on statistical analysis

Buck Creek Less Frequent plot 132 (formerly a control) was not included in the analysis as fire temperatures were not recorded during the burn. The bark scorch results have yet to be entered but were fairly high. They are located in the 2003 fuels fieldbook. Chestnut Cliff Less Frequent plot 85 was not included in the analysis as temperature tags were not placed on the plot before the burn and very little (<10%) of the plot burned. Additionally, Chestnut Cliffs frequent plot 141 and Buck Creek Less Frequent plot 99 were removed from the data set as very little of the plots burned (<10%).

Before analyzing the data set, all trees that were dead in 2002 were removed from the data set. When scorch heights were measured in May of 2003 we did not bother to record char on trees that looked like they had been dead in 2002, but we did not have the 2002 data set with us to confirm this. This unfortunately was a check sheet-less method, as we had entered the trees in the palm pilot, resulted in a failure to record scorch on some trees that were near dead in 2002. These errors or oversights can be seen in difference of numbers of trees with char width at 30 cm measured (which was recorded during overstory measurement) but without highest char measurements.

Table 1: Mean DBH of species graphed

Species	Mean DBH	Standard error	Mean(desw/o0)	Standard error
sugar maple	8.2066	0.4683	0.252778	0.023515
serviceberry	7.1953	0.5507	0.40125	0.047708
dogwood	6.9882	0.7838	0.407647	0.066167
red maple	11.4296	0.4112	0.43905	0.027504
white oak	25.8199	1.5635	0.638452	0.07056
n. red oak	30.3158	2.4014	0.6476	0.087383
hickories	21.7067	1.2414	0.704943	0.078192
blackgum	8.3103	0.9306	0.774368	0.086859
scarlet oak	25.6812	1.1943	0.80725	0.105058
chestnut oak	31.3475	2.0742	0.992866	0.062259
sourwood	10.2627	0.6370	1.028	0.160749
yellow poplar	29.9725	2.7159	1.1175	0.214451
black oak	38.5353	1.9628	1.201961	0.184737

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