Characterization of Fuel before and after a Single Prescribed Fire in an Appalachian Hardwood Forest

Elizabeth Loucks, Mary A. Arthur, Jessi E. Lyons, and David L. Loftis

ABSTRACT

Improved understanding of how fuel loads and prescribed fire interact in Appalachian hardwood forests can help managers evaluate the impacts of increased use of prescribed fire in the region. The objective of this study was to characterize fuel loads before and after a single late-winter/early spring prescribed fire and after autumn leaf fall. A repeated measures split-plot design was used to examine dead and down fuels by treatment, sampling time, and landscape position. Preburn mean fuel mass was 40.5 Mg/ha with the duff (Oea) comprising the largest component (19.5 Mg/ha; 48%), followed by large (more than 7.6 cm in diameter) downed logs (9.6 Mg/ha; 24%). Fuel mass was similar across landscape positions; however, duff depth was greater on subxeric compared with intermediate and submesic landscape positions. Burning reduced litter mass (Oi; $P < 0.001$) and duff depth ($P = 0.01$). Changes in woody fuels (1-, 10-, 100-, and 1,000-hour) and duff mass were not statistically significant. Post–leaf fall fuel masses did not differ from preburn masses. Thus, a single prescribed burn did not accomplish significant fuel reduction. However, significant declines in duff depth and fuel bed continuity may limit the spread of fire beyond leaf fall and increase potential for soil erosion. This study contributes to the dialogue regarding the use of fire in the Appalachian forest region and impacts on fuel loads.

Keywords: forest floor, litter, duff, landscape position, fuel continuity

Paleontological data indicating that surface fires have occurred in Appalachian forests for the past 3,000 years (Delcourt et al. 1998), combined with suggestions that prescribed fire may be an effective tool for improving regeneration of oaks (Van Lear and Watt 1993), have led to increased use of prescribed fire in the central Appalachian region (Brose et al. 2001). The increased use of fire

decomposition relative to fuel deposition rates in Appalachian hardwood forests (MacMillan 1981, Mudrick et al. 1994) often leads to relatively low total fuel loads even in the absence of fire. Immediate reductions in litter mass after a single prescribed fire have been reported for central and Appalachian hardwood forests (Clinton et

this region reflects the views of many forest managers who consider fire a potentially important tool for thinning overstocked forest stands, encouraging oak seedling establishment, and reducing fuels (Brose et al. 2001).

Prescribed fire is used worldwide to reduce 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, little research has been done to characterize fuel loads in hardwood forests on the Cumberland Plateau (Chojnacky and Schuler 2004) or to assess the reductions in fuels after prescribed burning. Research on fuels in the larger central and Appalachian hardwood regions provides insufficient evidence to support the contention that prescribed fire significantly reduces fuel loads (Thor and Nichols 1973, Franklin et al. 1995, Hartman 2004, Graham and McCarthy 2006, but see Hubbard et al. 2004 and Kolaks et al. 2004) or alters the ability of the fuels to carry fire repeatedly (Thor and Nichols 1973, Huddle and Pallardy 1996). In addition, rapid al. 1998, Kolaks et al. 2004, Graham and McCarthy 2006). However, the longer-term effects of fire on fuel accumulation, even just leading up to the next fire season, are not well described. Nonetheless, "hazard-reduction" burns are considered an additional benefit of management fires in central and Appalachian hardwood forests (Van Lear and Waldrop 1989). With increased forest burning by land managers in the central and Appalachian hardwood regions, an improved understanding of the effects of fire on fuel loads must accompany studies that focus on the ecological effects of burning.

In the 1990s, managers in the Daniel Boone National Forest (DBNF), Kentucky, began using prescribed fire for a range of management objectives, including "habitat manipulation and fuel reduction" (US Forest Service 2004). This study was designed to characterize the down and dead fuel load in an Appalachian hardwood forest in Kentucky and to evaluate the effect of landscape position and prescribed fire on fuel load. Fire can alter the future fire regime through reduction in the risk of unplanned fire, ability of fuels to carry a fire, or changes in fire intensity (Graham and McCarthy 2006), with potential implications for future management

Received June 6, 2007; accepted February 27, 2008.

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using prescribed fire. We hypothesized that litter (Oi) and duff (Oea) accumulation would vary topographically, with higher accumulations on lower slope positions due to the redistribution of leaf litter downslope after leaf fall (Orndorff and Lang 1981, Boerner and Kooser 1989). Second, we hypothesized that fuel reduction from a single prescribed fire would occur primarily in the litter layer and small woody fuels. Third, we hypothesized that fuel reductions would vary by landscape position, with drier slope positions having more intense fires and therefore a greater reduction in fuels. Finally, we hypothesized that fuel loads 10 months after the prescribed fires would be similar to preburn fuel loads, reflecting the replenishment of the primary fuel bed from autumn leaf fall.

Methods

Site Description

Three study sites were chosen within the Morehead Ranger District of the 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 of 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 1,180 ft) and encompasses slopes of varying aspect in each study area. Soils are also variable in depth and texture because of the steep unglaciated topography and are classified as Typic Hapludults, Typic Hapludalfs, Ultic Hapludalfs, and Typic Dystrochrepts (Avers 1974). The forest stands within the study sites are approximately 80 years of age and vary widely in site index (based on white oak, base year 50) across landscape positions (from site index 50 to 110). The landscape

Table 1. Plots are allocated to study sites, burn treatments, and landscape positions as shown.

Site	Area (ha)	Submesic	Intermediate	Subxeric	Total
Buck Creek					
Fire excluded	73	3	3	4	10
Burned	158	4	11	8	23
Chestnut Cliffs					
Fire excluded	61	6	3	0	9
Burned	133	6	11	2	19
Wolf Pen					
Fire excluded	74	8	2	0	10
Burned	219	5	10	5	20
Total		32	40	19	91

Experimental Design

Each study site was subdivided into three treatment units for use in a long-term study of the effects of prescribed fire on oak regeneration: two of the treatment units were treated with prescribed fire in 2003 and one served as a fire-excluded treatment. Treatment areas within each study site were delineated by natural variation in topography and road systems and, thus, varied in size (55–117 ha/treatment unit or 61–193 ha with burn treatments combined for each site; Table 1). Within each treatment area, sample plots were systematically located from a grid overlain on a topographic map using a stratified random design. The number of plots (8–12) reflected the size of the treatment area, for a total of 93 plots. Two plots were not used in the analysis because of data loss, resulting in a total of 91 plots. The plots were 10 × 40 m and oriented parallel to the topographic contour along the longitudinal axis.

For this study, the two burn treatments were combined into one treatment unit, "burned." The combination of two treatments into one resulted in an unbalanced design with approximately twice as

consists of steep slopes and undulating topography resulting in variation in site moisture conditions from shallow coves to exposed ridges. Stands are dominated by oaks (*Quercus* spp.) and hickories (*Carya* spp.) in the overstory; however, there is considerable variability in species composition among stands.

Plots were categorized into landscape positions (subxeric, intermediate, and submesic) after site selection using an expert system of site classification based on tree species composition (McNab et al. 2007). Briefly, this classification system follows the rationale of Whittaker (1956) by arraying all arborescent species according to their perceived moisture requirements along a continuous gradient quantified from 1 (xeric) to 4 (mesic). The landscape position of each sample plot was determined by calculating the mean gradient value of all tree species present from a standard inventory, i.e., mean values based on presence–absence of species rather than abundance. Plots with mean gradient value of 2.20 or less were categorized as subxeric and those with values of 2.71 or more were assigned the category submesic; others were classified as intermediate. Submesic sites are dominated by oaks (*Quercus alba*, *Q. prinus*, *Q. rubra*, and *Q. velutina*), sugar maple (*Acer saccharum*), and hickories and yellow poplar (*Liriodendron tulipifera*); other species have less than 10% relative density in stems of more than 10-cm dbh. Subxeric sites are dominated by oaks (*Q. alba*, *Q. coccinea*, *Q. prinus*, and *Q. velutina*) and red maple (*Acer rubrum*), and intermediate sites are dominated by oaks (*Q. alba*, *Q. coccinea*, *Q. prinus*, *Q. rubra*, and *Q. velutina*), hickories, and red maple. These sites have not been burned by wildfire or prescribed fire in the last 30 years (Michael Colgan, US Forest Service, Morehead, KY, pers. comm., Mar. 21, 2008).

many plots in the burned treatments as the fire-excluded treatments.

Fire Prescription and Temperature Measurements

US Forest Service personnel of the DBNF conducted the prescribed fires in March and April of 2003 using drip torches and helicopter ignition, which led to a combination of head, strip, and backing fires. Nineteen plots in the Chestnut Cliffs area were burned on 2 consecutive days, Mar. 24 and 25, 2003. Twenty-three plots in the Buck Creek area were ignited on Apr. 14, 2003 and 20 plots in the Wolfpen area were burned on Apr. 16, 2003. Ambient weather conditions are given in Table 2. Flame lengths and rates of spread were highly variable within and between burn treatments because of ignition along lower slope, midslope, and ridge positions. Burn personnel observed flame lengths varying between 2 and 3 ft throughout much of the burn areas, increasing to 5–6 ft during gusts, and up to 6–8 ft on some areas of steeper slopes that were ignited toward the base of the slope.

Fire temperature data recorded during prescribed fires 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, Iverson et al. 2004). Since it was not possible to systematically record flame length and rate of spread during burning because of 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 (Tempil, South Plainfield, NJ) representing temperature ranges from 79°C to

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: BC, WP, and CC.

Conditions	CC south	CC north	BC	WP
Burn date	Mar. 24, 2003	Mar. 25, 2003	Apr. 14, 2003	Apr. 16, 2003
Time of ignition	12:30	11:30	11:30	12:30
Air temperature (°C)	24	25	26	27
Relative humidity (%)	35	33	23	39
Wind direction	W	SW	NW	W
Wind speed (km/hr)	0–9	0–10	0–10	0–14
10-hour fuel moisture (%)	18	14	15	11
Pyrometer	CC south (n = 10)	CC north (n = 9)	BC (n = 23)	WP (n = 20)
0-cm mean (°C)	475	476	523	575
Range	(87–536)	(20–617)	(43–644)	(469–644)
20-cm mean	233	283	230	313
Range	(115–359)	(20–536)	(67–466)	(150–550)
40-cm mean	158	211	165	225
Range	(49–269)	(20–442)	(63–353)	(97–370)

BC, Buck Creek; CC, Chestnut Cliffs; WP, Wolfpen.
CC south and CC north are shown separately because they were burned on different days. For burn temperature data, ranges represent the mean maximum temperatures of individual plots within burn unit.

Table 3. Mean maximum temperature (°C) surpassed at three heights above forest floor (0, 20, and 40 cm) for the three landscape positions: submesic, intermediate, and subxeric.

Pyrometer (cm)	Subxeric (n = 15)	Intermediate (n = 32)	Su-mesic (n = 15)
0	561.8[a]	561.9[a]	447.9[b]
	(17.4)	(11.8)	(43.0)
20	307.8[a]	289.8[a]	195.9[b]
	(35.5)	(17.7)	(28.1)
40	231.9[a]	203.6[a]	135.5[b]
	(27.4)	(13.8)	(18.4)

Standard errors are given in parentheses.
[a,b] Significant differences at $P < 0.05$ between landscape position within each height.

Overall, fires conducted in this study can be characterized as low to moderate intensity surface fires.

Fuel Measurements

Two methods were used to estimate the fuel loading of down and dead material: planar intercept transects and forest floor blocks. A measure of forest floor mass was obtained in January and February 2003, by systematically collecting 0.073-m^2 (27 × 27 cm) sections of the forest floor from four locations positioned 1 m from the planar intercept transects (described later) and the boundary of each plot. When the predetermined location of a block crossed woody material greater than the 10-hour timelag size class (2.54-cm diameter), the block was moved the smallest distance necessary (regardless of direction) to an area free of woody material of this size. Thi

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 10 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 (644°C) extended the temperature range. The pyrometers were collected within 4 days of the fires. Mean minimum fire temperatures on each plot were estimated by averaging the highest temperature surpassed on each pyrometer. If none of the paints melted, an ambient air temperature of 20°C was used when calculating the mean temperature surpassed. Temperatures were variable because of 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 16) had the hottest mean temperatures (Table 2). Temperatures differed by landscape position with submesic plots having the lowest mean temperatures surpassed at all three heights from the soil surface (Table 3).

Tree mortality after burning was recorded also and yields a general sense of the variability in fire intensity across landscape positions (Green 2005). Using mortality of stems of 2- to 10-cm dbh as a surrogate for fire intensity, we found differences in fire intensity among the three landscape positions. Mortality of stems of 2- to 10-cm dbh was 88% in subxeric sites, 66% in intermediate sites, and 34% in submesic sites, paralleling our findings of lowest fire temperatures in submesic plots. Overstory mortality (defined as stems of more than 20-cm dbh), although generally low, also varied among landscape positions and sites. Subxeric sites had overstory mortality of 19%, whereas on submesic sites there was no overstory mortality.

occurred on fewer than 5% of the sampling points, introducing little, if any, bias in the results. The litter (Oi) layer was removed and bagged separately from the duff. Wood, bark, and fruits were removed from the litter and bagged separately in the laboratory. All forest floor material was dried at 60° C for 48 hours and then weighed. Forest floor was resampled within 2 weeks after the prescribed fires of 2003 and after autumn leaf fall in January and February of 2004, in new locations 1 m away from the previous sample point.

A measure of the woody fuel loading was obtained by tallying fuel classes along planar intercept transects before the prescribed fires in January and February of 2003 and on the same transects within 1 month after prescribed fires, and again 10-months postburn (referred to as post–leaf fall) in January and February 2004 (Van Wagner 1968, Brown 1974). Woody fuels were tallied in four diameter size classes along sampling lengths based on Brown (1974). Fuel classes were nested along two 17-m transects with 1-hour (0–0.635 cm in diameter) and 10-hour (0.635–2.54 cm in diameter) timelag fuels tallied along 2 m, 100-hour (2.54–7.62 cm in diameter) timelag fuels tallied along 4 m, and 1,000-hour (more than 7.62 cm in diameter) rotten and solid timelag fuel diameters measured along the full 17 m. Transects were perpendicular to each other and located at opposite ends of each plot in locations that received minimal disturbance during the installation of the plots and during the initial measurements of overstory trees. For 1-hour fuels there is the potential that, before burning, some 1-hour fuels may be hidden beneath the litter that are then exposed after burning, leading to an underestimate of the consumption of fuels in this size class. To avoid

Table 4. Mean mass of preburn fuel load components on all plots and by the three landscape positions: submesic, intermediate, and subxeric.

	Litter	Duff (Oe and Oa)	Duff depth	1 hr	10 hr	100 hr	1,000 hr	Total
All Plots (n = 91)	3.1 (0.08)	19.5 (0.7)	2.5 (0.13)	0.59 (0.04)	2.7 (0.22)	5.0 (0.45)	9.6 (1.28)	40.5 (1.72)
Sub-mesic (n = 32)	3.1 (0.10)	17.1 (1.32)	2.1 (0.11)[a]	0.59 (0.07)	2.7 (0.42)	5.4 (0.86)	10.6 (2.55)	39.4 (3.63)
Intermediate (n = 40)	3.2 (0.12)	20.1 (0.94)	2.3 (0.11)[a]	0.60 (0.06)	2.6 (0.33)	4.9 (0.69)	8.3 (1.42)	39.6 (2.01)
Sub-xeric (n = 19)	3.1 (0.21)	22.6 (1.30)	3.4 (0.14)[b]	0.57 (0.07)	3.1 (0.36)	4.4 (0.63)	10.4 (3.29)	44.1 (3.58)

Standard errors are given in parentheses.
[a,b] Significant differences at $P < 0.05$ among landscape positions within fuel component. Units are Mg/ha, except for duff depth, which is in cm. Note that all columns except "duff depth" add to yield the total fuel mass.

this potential problem, we palpated the litter for 1-hour fuels and included those fuels in the transect tallies. Thousand-hour fuels were initially separated into rotten and solid fuels, because of the expected differences in specific gravity. However, because of difficulty in determining condition class during the winter when wet logs were frozen, rotten and solid logs were combined into a single 1,000-hour woody fuel class. Woody fuel load weight (w) was calculated by converting the number of intersections tallied to mass/area for size classes using Brown's (1974) formulas. Specific gravity (s) was estimated for the 1-, 10-, and 100-hour timelag fuel class based on Anderson (1978) for southern and southeast forest types as follows: 1- and 10-hour, 0.7; 100-hour, 0.58. Specific gravity for 1,000-hour fuels was based on the ratios of rotten and solid 1,000-hour fuels found on our study sites and on specific gravity values used in central hardwood forests. Based on values found in Franklin et al. (1995) of $s = 0.58$ for solid and 0.30 for rotten 1,000-hour fuels, we applied 0.58 and 0.30 to the proportion of solid and rotten wood measured in 2003, a sampling period for which we were most confident in our delineation of solid versus rotten, resulting in a weighted mean value of 0.40 that we applied to all 1,000-hour fuels. The depth of duff

predicted means to obtain P-values, the actual descriptive means are presented in the results. Analysis of variance was used to test for differences in the coefficient of variation of the plot litter mass between treatment and sampling period to determine if the continuity of forest floor litter was altered by burning.

Results

Fuel Characterization

Mean preburn fuel load averaged 40.5 Mg/ha. The largest component of the fuel bed was duff, followed by 1,000- and 100-hour woody fuels (Table 4). Together, duff and 100- and 1,000-hour fuels comprised approximately 84% of the total fuel load. The smallest component of the fuel load was 1-hour fuels (1.4%), and leaf litter fuels comprised 7.6% of the total fuel load and 10-hour fuels comprised another 6.8%. Because some studies include the mass of fruits and bark in the litter fuels category, we estimated litter mass with these components as well, for comparative purposes. With mass of fruits and pieces of bark included, mean litter mass was 0.28 Mg/ha or 9% heavier; however, for all subsequent data, we only

(Oea) was measured at 0.5 and 1.5 m on each of the two transects per plot, providing a nondestructive sampling of change in duff depth. 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.

Statistical Analysis

Mean fuel load and duff depth measured in 91 plots were analyzed using a repeated measures, split-plot analysis in PROC MIXED in SAS (SAS Institute 1999). Fixed effects included site, treatment (burned or fire excluded), time of measurement (preburn, postburn, and post–leaf fall), and landscape position, with fire treatment as the whole-plot factor and landscape position as the split-plot factor. Satterthwaite's approximation was used for calculating degrees of freedom and site was treated as a random effect. Seven fuel components and their sum were tested with the model. These components included leaf litter with dead herbaceous material; duff (Oea) mass; duff depth; and the 1-, 10-, 100-, and 1,000-hour timelag woody fuel classes. Each fuel component was modeled separately to test for main effects (treatment, time, and landscape position) and four interactions (treatment and sample period; treatment and landscape position; landscape position and sample period; and the interaction of treatment, landscape position, and sample period). When main effects were found to be significant, pairwise *t*-tests of predicted means were used to obtain probability values for the differences between the predicted means of fuel load mass for the different treatments, landscape positions, and time; value of $P < 0.05$ were considered significant. Although we used the model's used leaf litter and dead herbaceous mass in our analysis of litter fuels. Mean duff depth averaged 2.5 cm.

Total fuel load did not vary significantly ($P = 0.50$) by landscape position (Table 4) nor did any of the separate components of the fuel. There was a significant effect of landscape position on duff depth ($P < 0.001$); duff depth was greater in plots on subxeric landscape positions compared with either submesic ($P < 0.001$) or intermediate positions ($P < 0.001$; Table 4).

Postburn Fuel Change

Of the individual fuel components analyzed with the repeated measures split-plot analysis, only litter ($P < 0.001$) and duff depth ($P = 0.01$) were reduced by prescribed fire, with litter having the highest percent reduction of the individual fuel loads (Table 5). There was both a significant effect of time ($P < 0.001$) and an interaction of time by treatment ($P = 0.004$) on litter fuels, with a reduction occurring between pre- and postburn measurements regardless of treatment. Litter decreased from 3.2 to 0.4 Mg/ha ($P < 0.0001$) on the burn treatments and from 2.9 to 2.1 Mg/ha ($P < 0.0001$) on the fire-excluded treatments (Table 5). This resulted in a 60% difference in litter reduction between treatments attributable to the effect of fire (Figure 1A). The large reduction of litter from fire-excluded plots suggests that as much as 28% of the reduction in litter on the burn treatments was the result of decomposition occurring between the pre- and postburn sampling periods, assuming that decomposition rates are similar on the burned and fire-excluded sites.

Duff depth decreased 36% on burn treatments to 1.69 cm ($P = 0.002$), whereas there was no significant change in duff depth on

Table 5. Changes in mean fuel loading between preburn and immediate postburn sampling periods in 2003 on burned and fire-excluded treatments for six fuel components and the total fuel load, given in Mg/ha (duff depth in cm) and as a percent of preburn fuel load.

	Litter (Oi)	Duff (Oea)	Duff depth	1-hr	10-hr	100-hr	1,000 hr	Total
Burned All treatments	−2.81[a] (88%)	−2.60 (13%)	−0.95[a] (36%)	−0.13 (21%)	−0.56 (20%)	−0.75 (14%)	−0.79 (8.2%)	−7.65[a] (14%)
Submesic	−2.33[a] (73%)	+0.53 (16%)	−0.46 (19%)	−0.08 (22%)	+0.14 (18%)	+1.12 (11%)	+1.04 (25%)	+0.42 (4.2%)
Intermediate	−2.33[a] (92%)	−3.79 (17%)	−0.84[a] (35%)	−0.13 (21%)	−0.55 (15%)	−1.30 (11%)	−1.00 (20%)	−9.74[a] (16%)
Subxeric	−2.97[a] (95%)	−3.2 (0.6%)	−1.7[a] (49%)	−0.17 (19%)	−1.28 (33%)	−1.47 (27%)	−2.19 (15%)	−11.27[a] (19%)
Fire-excluded All treatments	−0.83[a] (28%)	−0.08 (0.5%)	+0.17 (8.3%)	+0.11 (21%)	−0.09 (3.8%)	−0.68 (16%)	−0.68 (7.4%)	−2.25 (6.0%)
Submesic	−1.00[a] (33%)	+0.95 (5.9%)	+0.09 (4.7%)	+0.07 (13%)	−0.23 (9.7%)	−1.08 (22%)	+0.03 (0.3%)	−1.25 (3.5%)
Intermediate	−0.74 (27%)	−2.17 (11%)	+0.42 (27%)	+0.08 (14%)	+0.33 (15%)	+0.19 (7.7%)	−2.56 (29%)	−4.87 (13%)
Subxeric	−0.27 (9.2%)	−0.26 (1.1%)	+0.16 (4.7%)	+0.37 (69%)	−0.37 (10%)	−0.77 (14%)	+0.05 (0.5%)	−1.26 (2.9%)

Note that all columns except "duff depth" add to yield change in total fuel mass.
[a] Significant changes at $\alpha = 0.05$ level.

fire-excluded treatments ($P = 0.39$; see Figure 3). Preburn differences in duff depth with landscape position ($P < 0.001$) disappeared after burning (intermediate versus submesic, $P = 0.34$; subxeric versus submesic, $P = 0.50$; subxeric versus intermediate, $P = 0.49$).

Losses in other fuel components were nonsignificant. Although there was not a significant change in 10-hour woody fuels across sites, there was a significant difference in 10-hour woody fuels among landscape positions after burning, whereas no differences were detected before burning. After burning (on burned treatments), subxeric (1.7 ± 0.36 Mg/ha) and intermediate (2.1 ± 0.27 Mg/ha) plots had significantly less 10-hour fuel mass than submesic

cluded plots. In contrast, duff depth in burned plots was initially 32% greater than fire-excluded plots before burning ($P = 0.02$). Post–leaf fall duff depth had a similar trend with landscape position as that found in the preburn sampling. In burned plots, duff depth was greater in subxeric than on intermediate ($P = 0.04$) and submesic ($P = 0.03$) landscape positions, and the same was found on fire-excluded plots ($P = 0.004$ and $P = 0.005$, for subxeric versus intermediate and subxeric versus submesic, respectively). Duff depth on fire-excluded treatments was greater than on burned treatments on submesic ($P = 0.05$) and subxeric ($P = 0.01$) landscape positions. No other effects of landscape were significant for the

plots (3.2 ± 0.32 Mg/ha; $P = 0.004$ and $P = 0.02$, respectively; Figure 2). The combined fuel load, incorporating all fuel components, was significantly reduced by a single fire (Table 5). This reduction is the result of significant reductions in intermediate and subxeric sites, not submesic, which had a small, nonsignificant increase in fuel mass. Thus, despite a lack of statistically detectable decreases in fuel mass within individual components (except for litter), the accumulated decreases across fuel components resulted in a statistically significant decline in total fuel mass.

Post–Leaf Fall Fuel Load

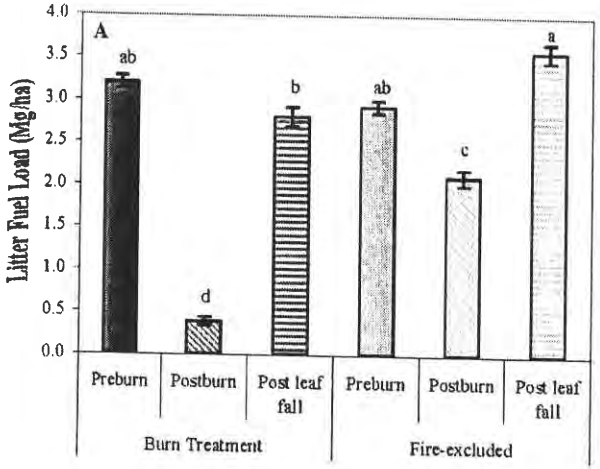
Ten months after burning, or post–leaf fall, the mean mass of several fuel components was found to have changed compared with the postburn measurements. Across all treatments, litter masses were higher in the post–leaf fall ($P < 0.0001$) than in the immediate postburn sampling period, reflecting the addition of new leaf litter (Figure 1A). Additionally, post–leaf fall litter mass on both treatments was similar to preburn masses ($P = 0.53$). 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 with the preburn sampling period ($P = 0.02$).

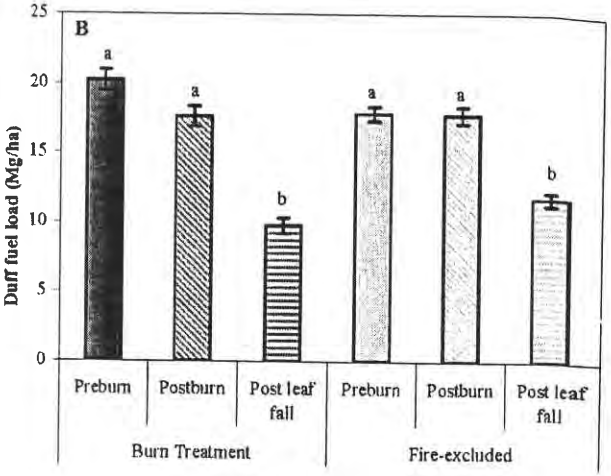
Although postburn duff masses were not different from preburn masses, duff mass had decreased by the post–leaf fall sampling period, again, regardless of treatment (Figure 1B; effect of time, $P = 0.03$). Post–leaf fall, duff depth was 41% lower than preburn depth in the burned treatments ($P = 0.001$), but remained unchanged in the fire-excluded treatments (Figure 3). Duff depths in burned plots sampled post–leaf fall were 30% lower ($P = 0.02$) than in fire-ex- post–leaf fall sampling period.

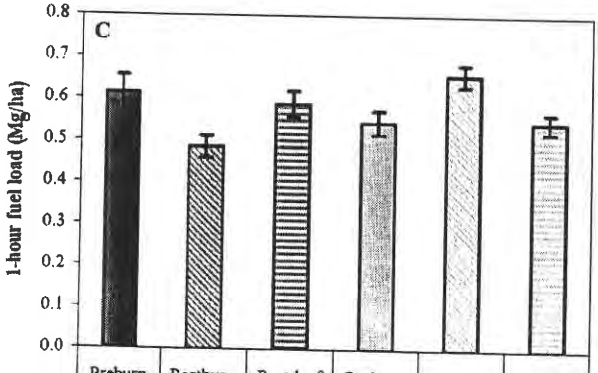
Woody fuels also varied with sampling period. Although there were no significant differences in 1-hour fuels among sampling dates for either treatment (Figure 1C), there was a trend toward reduction in 1-hour fuels after burning ($P = 0.17$), followed by recovery of 1-hour fuel mass after leaf fall ($P = 0.23$). There was a significant difference among sampling periods for 10-hour fuel mass ($P < 0.001$), with a higher mean mass found in the post–leaf fall sampling period (3.17 ± 0.2 Mg/ha) than in the preburn (2.73 ± 0.2, $P = 0.08$) and postburn (2.3 ± 0.16 Mg/ha, $P < 0.0001$) sampling periods (Figure 1D). These differences were found regardless of treatment, indicating an increase in 10-hour fuels across all treatments. Thousand-hour fuel mass also varied with sampling period. Post–leaf fall mass was somewhat higher compared with postburn fuel mass ($P = 0.01$) but not significantly different from preburn fuel mass ($P = 0.10$; Figure 1F), with no effect of treatment ($P = 0.98$).

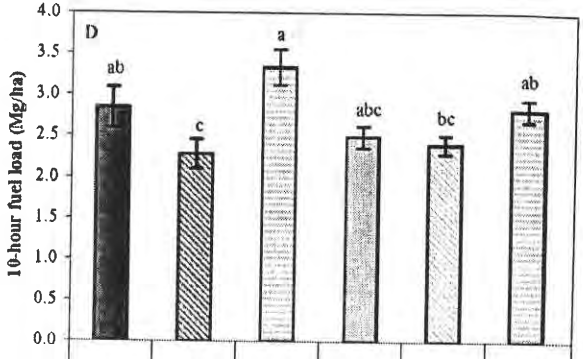
Discussion

We hypothesized that litter and duff accumulation would vary topographically, with greater litter fuel loads on lower slope, submesic landscape positions. We found a lack of variability in litter accumulation across landscape positions, coupled with greater duff depth on the subxeric plots compared with the submesic and intermediate plots, the opposite of what we hypothesized. Greater amounts of duff on subxeric positions may be the result of slower decomposition because of low moisture availability and lower litter


A
Litter Fuel Load (Mg/ha)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ab
d
b
ab
c
a
Preburn
Postburn
Post leaf fall
Preburn
Postburn
Post leaf fall
Burn Treatment
Fire-excluded


B
Duff fuel load (Mg/ha)
25
20
15
10
5
0
a
a
b
a
a
b
Preburn
Postburn
Post leaf fall
Preburn
Postburn
Post leaf fall
Burn Treatment
Fire-excluded


C
1-hour fuel load (Mg/ha)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0


D
10-hour fuel load (Mg/ha)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ab
c
a
abc
bc
ab

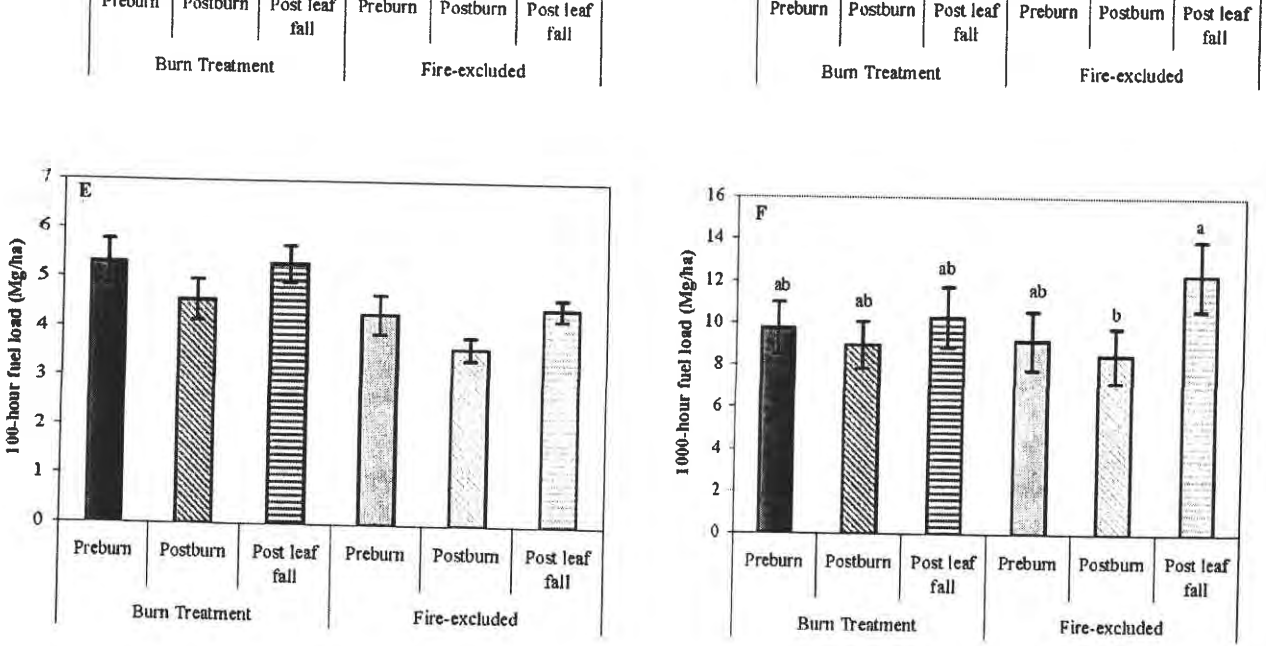


Figure 1. Mean fuel loads on burned (n = 61) and fire-excluded (n = 30) treatments, across all study sites, measured before prescribed fires in 2003 (preburn), immediately after prescribed fires in 2003 (postburn), and 10 months after the prescribed fires in early 2004 (post–leaf fall), for (A) litter, (B) duff, (C) 1-hour fuels, (D) 10-hour fuels, (E) 100-hour fuels, and 1,000-hour fuels. Lower case letters denote significant differences ($P < 0.05$) in fuel mass across all sampling periods and both treatments. There were no significant differences in 1-hour or 100-hour fuel masses.

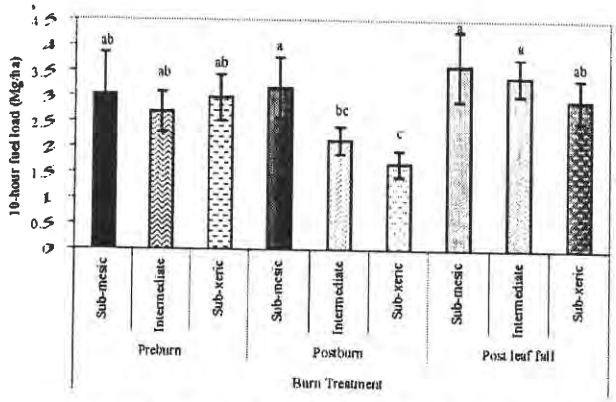
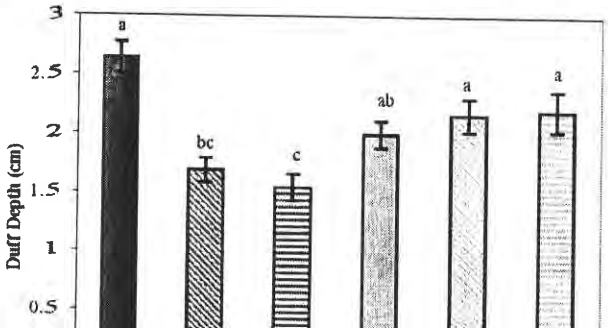


Figure 2. Mean 10-hour timelag woody fuel loads on burned and fire-excluded treatments before prescribed fires in 2003 (preburn), immediately after prescribed fires in 2003 (postburn), and 10 months after prescribed fire in early 2004 (post–leaf fall), separated by landscape position (submesic, intermediate, and subxeric). Different lower case letters denote significant differences ($P < 0.05$) across all landscape positions, sampling periods, and both treatments.



Previous studies have noted higher accumulation of coarse woody debris on lower slope positions than in other areas of dissected landscapes and have attributed this to dead logs falling and moving downslope (Harmon 1984, Kolaks et al. 2003, Rubino and McCarthy 2003). We found no statistically significant difference among landscape positions in the mass of 1,000-hour timelag fuels, the size class that is comparable to the "coarse woody debris" component measured in studies without a fuels focus.

Our hypothesis that fuel reduction from a single prescribed fire would occur primarily in the litter layer and in small woody fuels was partially correct. Our finding of a statistically significant reduction in litter mass after burning complements previous reports of fuel reductions in southern Appalachian and central hardwood forests (Wendel and Smith 1986, Franklin et al. 1997, Clinton et al. 1998, Hubbard et al. 2004, Kolaks et al. 2004, Graham and McCarthy 2006). However, some studies also have documented significant reductions in 1- and 10-hour fuels (e.g., Kolaks et al. 2004), which we did not find in this study. We did find a significant decrease in duff depth in response to fire. In addition, preburn differences in duff depth with landscape position disappeared after burning, strongly suggesting that more duff was combusted on intermediate and subxeric plots compared with submesic plots. Nondestructive duff depth measurements were made in the same locations before and after fire, and may provide a somewhat more accurate assessment of duff consumption (lower sampling variability) than the forest floor blocks, which were destructive measurements made in different locations each time.

Although dead, down woody fuels are a potentially important fuels component, influencing fire spread and duration (Pyne et al. 1996), changes in large, down woody fuel loads by prescribed fire have not been reported as frequently as for fine fuels. We found no significant changes in 10-hour fuels and the mean mass of 100-1

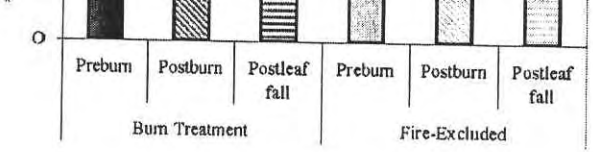


Figure 3. Mean duff depth on burned and fire-excluded treatments before prescribed fires in 2003 (preburn), immediately after prescribed fires in 2003 (postburn), and 10 months after prescribed fire in early 2004 (post–leaf fall). Lower case letters denote significant differences ($P < 0.05$) in duff depth across all sampling periods and both treatments.

quality compared with submesic sites with higher moisture retention and higher litter quality (Mudrick et al. 1994). Subxeric landscape positions were dominated by oak and ericaceous species that generally have high lignin content in their litter compared with species dominating the submesic landscape positions, such as sugar maple and yellow-poplar (Melillo et al. 1982, Mudrick et al. 1994). Earthworm activity on plots with moist and nonsandy soils may have resulted in lower humus accumulation on submesic and intermediate landscape positions when compared with the drier and rockier subxeric plots. Although earthworm abundance was not measured, earthworms were encountered more often on intermediate and submesic plots. Differences in litter mass were not found among landscape positions in this study as we had hypothesized, although downslope movement of litter could be expected for hardwood stands on steep slopes (Orndorff and Lang 1981, Boerner and Kooser 1989). We also found no significant difference among landscape positions in the amount of woody fuels, regardless of size class.

significant changes in 10-hour fuels, and the mean mass of 100-hour fuels on our burn treatment decreased from 5.3 to 4.6 Mg/ha postburn, but not significantly ($P = 0.28$), and returned to preburn levels by the post–leaf fall measurements. Kolaks et al. (2004) found decreases in 100- and 1,000-hour fuels similar in magnitude to those observed on our sites, but also nonsignificant ($P > 0.05$). Graham and McCarthy (2006) also found significant reduction in litter mass after a single prescribed fire and no reduction in other fuel components. It is worth noting that prescribed fires may increase the woody fuel load after burning because of increased mortality.

Finally, we hypothesized that fuel loads after autumn leaf fall and earlier prescribed burning would be similar to preburn fuel loads. We found that post–leaf fall litter mass was similar to preburn levels; thus, fires did not have a lasting impact on litter mass. Collection of forest floor blocks is seasonally sensitive, ideally occurring after autumn leaf fall is complete, and before early spring decomposition. This seasonal window corresponds with freezing temperatures; thus, 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. Greater attention to the potential problem of accurate separation during post–leaf fall sample collection the following year almost certainly contributed to the consistently lower duff mass for this sampling period across all treatments, and likely does not signify an actual reduction in duff mass in both fire-excluded and burn treatments. This is supported by the lack of change in duff depth on fire-excluded plots during the study. On the burned treatments, duff depth did not recover to preburn levels post–leaf fall, however, suggesting

that duff loss may be exacerbated by other factors after fire such as heavy-rain events and wildlife disturbances.

Fuel reduction may be one of a manager's goals for a stand if they are interested in reducing wildfire hazard or in conducting low-intensity prescribed fires in the future. There is little evidence in our data to suggest that a single prescribed fire, conducted within burn parameters in late winter or early spring, reduces wildfire hazard appreciably or reduces woody fuels. Disruption of fuel bed continuity may contribute more to a reduction in the immediate threat of wildfires than the reduction in the mean fuel load, because only 18% of the total mean fuel load on the burned plots was consumed (41.9—34.3 Mg/ha). In deciduous hardwood stands the 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. Our finding of significantly higher coefficient of variation of the litter mass from individual plots after autumn leaf fall suggests a less continuous fuel bed despite the lack of a statistically detectable decrease in litter or duff mass. Van Lear and Waldrop (1989) reported that after a hazard-reduction burn in the Appalachians, stands usually were protected from wildfire until the next leaf fall, and the threat of wildfires was minor for 3–7 years afterward. However, hardwood forests have been burned annually in studies in Tennessee, Missouri, Minnesota, and Ohio (Thor and Nichols 1973, White 1983, Huddle and Pallardy 1996, Hutchinson et al. 2005). After 7 years, Thor and Nichols (1973) found that annually burned hardwood stands in Tennessee had lower leaf litter weights (2.5 Mg/ha) than unburned hardwood stands (6.8 Mg/ha) as a result of tree mortality. Unfortunately little information is available on the long-term effects of burning on woody fuels (Loomis and Crosby 1970, Hartman 2004). Decreased fuel bed continuity does reduce the capability of fuels to carry a fire, with implications for

icantly reduced by a single fire in our study, we suggest that its measurement is important when monitoring the effects of prescribed fire.

Conclusions

Contrary to our first hypothesis, litter fuel loads did not differ among landscape positions, and duff depths were greater on subxeric sites compared with submesic sites. This suggests that the drier conditions of these sites, compared with submesic sites, coupled with dominance by oaks and other species with decay-resistant foliage, supersedes the effects of downslope movement of leaves, leading to greater accumulation of partially decomposed organic material on subxeric sites.

We also hypothesized that a single fire would reduce litter and small woody fuels, and that fuel reductions would vary by landscape position with greater reduction of fuels on subxeric sites. Significant reduction in fuels occurred for litter across all landscape positions, whereas a decrease in duff depth was significant only on intermediate and subxeric landscape positions. Coupled with increased variability in litter mass, this may suggest potential for increased soil erosion after prescribed burning. A decline in total fuels also was statistically significant on intermediate and subxeric landscape positions.

Finally, we hypothesized that fuel loads after autumn leaf fall following prescribed burning would be similar to preburn fuel loads. We found that post–leaf fall litter mass returned to near preburn levels, suggesting that the fires did not have a lasting impact on fuel loading. Our study suggests that, beyond an increase in fuel discontinuity, a single late-winter, early spring prescribed fire of low to moderate intensity will do little to alter the future wildfire risk in stands similar to those studied here.

prescribed fire frequency.

We observed that eastern wild turkeys (*Meleagris gallopavo silvestris*) increased forest floor variability and therefore the continuity of the fuel bed on our study sites as well (personal observations). In future studies in this region it will be important to quantify the effects of turkeys on litter removal or movement, which can contribute to fuel bed discontinuity. Awareness of turkey activity on units for which burning is planned may aid managers in assessing the likelihood of discontinuity in the fuel bed.

Although 1,000-hour timelag fuels comprise a large portion of the total fuel load, it is important ecologically that these fuels were not significantly reduced on our study sites. Coarse woody debris, or large woody fuels, have importance to wildlife as habitat (Harmon et al. 1986, Ford et al. 1997), and the continuous release of minerals, such as Ca, Mg, and K, from decaying logs, may have important impacts on nutrient cycling and forest regeneration (Idol et al. 2001).

Our conclusion that duff was not reduced by burning is somewhat equivocal; although we did not measure a significant decrease in duff mass with burning, there was a significant decrease in duff depth. Combustion of the litter layer, without removal of the duff, may facilitate the establishment of oak seedlings (Garcia et al. 2002). The high retention of the duff on our study sites also should help maintain soil moisture and nutrients and prevent soil erosion by maintaining soil porosity. On the other hand, reduction in the depth of the duff layer signals the potential for increased soil erosion and for further effects from future burning. Given the fact that duff comprised 20% of total fuel loading and that duff depth was signif-

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