EFFECTS OF UNDERSTORY BURNING IN A MESIC MIXED-OAK FOREST OF THE SOUTHERN APPALACHIANS

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ABSTRACT

Information is lacking on ecosystem effects of understory burning in mesic mixed-oak (*Quercus* spp.) forests of the southern Appalachians. Native Americans used periodic fires in these forests for driving game and opening the forest. In April 1998, we conducted a low- to moderate-intensity fire in a cove–hardwood forest in the Nantahala National Forest, western North Carolina. In March 1998, before burning, permanent plots were established along three parallel transects to measure forest floor mass, carbon (C), and nitrogen (N); soil nutrient (NO_3^-, NH_4^+, PO_4^-, Ca, Mg, and K) availability; and vegetation mortality and regeneration. Forest floor material was sampled by components: small wood, litter (Oi), and a combined fermentation and humus component (Oe + Oa). Soil nutrient availability was estimated using cation and anion exchange membrane sheets. Vegetation measurements included the overstory and understory layers. All parameters were resampled during summer 1998 and 1999 in the same manner as the pre-burn inventories. Burning reduced the total mass, carbon, and nitrogen of the Oi layer by 92%, 93%, and 91%, respectively. Reductions in mass, carbon, and nitrogen of the Oe + Oa layer were 48%, 46%, and 56%, respectively. Burning resulted in increased exchangeable K, Ca, Mg, NH_4, PO_4, and NO_3 availability in soil on the burned area compared with the control. One year after burning, there were no significant differences in exchangeable nutrients between the burned and the control area. Overstory mortality was substantial, with 55% of the trees killed by the fire. However, most of the mortality occurred in trees <10 cm diameter at breast height (DBH) and no trees >20 cm DBH were killed. In the understory, all the aboveground stems were killed; although 50% of these individuals sprouted during the growing season (July 1998), some of these sprouts did not survive through the following year (July 1999). Moderate-intensity understory burning may be a useful tool to restore mesic mixed-oak communities in the southern Appalachians. Reintroduction of fire into these ecosystems may be beneficial by increasing soil nutrient availability, promoting regeneration and survival of *Quercus* spp., increasing diversity of understory species, and reducing abundance of shade-tolerant and fire-intolerant species such as *Acer rubrum*.

keywords: ecosystem analysis, forest floor, North Carolina, prescribed fire, population dynamics, soil nutrients, southern Appalachians.

Citation: Elliott, K.J., J.M. Vose, B.D. Clinton, and J.D. Knoepp. 2004. Effects of understory burning in a mesic mixed-oak forest of the southern Appalachians. Pages 272–283 *in* R.T. Engstrom, K.E.M. Galley, and W.J. de Groot (eds.). Proceedings of the 22nd Tall Timbers Fire Ecology Conference: Fire in Temperate, Boreal, and Montane Ecosystems. Tall Timbers Research Station, Tallahassee, FL.

INTRODUCTION

The forests of the southern Appalachians have developed under an extensive history of anthropogenic and natural disturbances. Native Americans burned extensive forested land areas for agriculture and hunting for thousands of years (Day 1953, Pyne 1983, DeVivo 1991). The Cherokees used periodic fires in these forests for driving game and opening the forest "to increase visibility, improve forage, expose the mast, and help keep down the weeds" (DeVivo 1991:307). Beginning in the mid-1800s European settlers also used fire, in combination with land clearing, and nearly the entire southern Appalachian region was logged during the early 1900s (Stephenson et al. 1993). About the same time, chestnut blight (*Cryphonectria parasitica*) decimated American chestnut (*Castanea dentata*) populations, which formerly occupied about 35% of the basal area of the oak–hickory (*Carya* spp.) forest type (Woods and Shanks 1959). Subsequent fire exclusion, smaller scale logging, and reversion of agricultural land to forest have further altered forests in the region.

The USDA Forest Service has made application of prescribed fire one of its priorities for restoration of forest ecosystems that have been altered by fire suppression, insect or disease outbreaks, or past management (Hardy and Arno 1996). Several studies have been conducted in pine–hardwood forests of the southern Appalachians on the effects of fire on ecosystem processes (Swift et al. 1993, Vose and Swank 1993, Vose et al. 1998) and vegetation dynamics (Barden and Woods 1976, Van Lear 1991, Elliott et al. 1999, Clinton and Vose 2000), but little information is available on the effects of understory burning in mesic mixed-oak forests. The USDA Forest Service is prescribing understory burns in these sites to reduce fuels, improve regeneration of tree species, particularly oaks, and increase understory diversity.

In the eastern U.S., the area of oak–hickory forest is diminishing due to succession and land use, and the importance of oak is decreasing within those forests. Problems and consequences of oak decline have been discussed (Loftis and McGee 1993), with fire suppression being associated with the decline of oak (Lorimer 1985, Crow 1988, Abrams 1992, Crow et al. 1994). Reintroduction of fire in these ecosystems should be beneficial to oaks (Van Lear et al. 2000). Relative to other hardwoods, fire should favor oaks because of their thick bark, sprouting ability, resistance to rotting after scarring, and the suitability of fire-created seedbeds for acorn germination (Lorimer 1985, Abrams 1996).

Forest floor mass, N, and C pools are an important reservoir of nutrients (Boerner 1982, Vose and Swank 1993) because they turn over rapidly and are the primary aboveground input to the soil. Fire in forested ecosystems generally decreases total ecosystem N (Rapp 1990, Vose and Swank 1993, Knoepp and Swank 1993). This loss is due to the volatilization of N contained in wood, leaf materials, and the forest floor during the fire (Knoepp and Swank 1993). However, effects of fire on N loss vary widely among forest systems due to several factors, including fire severity and duration, fuel type and load, and season of burn.

In this study, we examined the effects of a single dormant-season prescribed fire on forest floor consumption, soil nutrient availability, and vegetation dynamics (mortality, regeneration, and diversity) in a southern Appalachian mesic mixed-oak ecosystem. We hypothesized that a low-to-moderate intensity understory fire would increase soil nutrient availability, stimulate regeneration of desirable oak species, and reduce the abundance of fire-sensitive woody species.

STUDY AREA

The study area was located on the Nantahala National Forest in the southern Appalachian region of western North Carolina (lat 35°00′N, long 83°24′W). The study site was a 5-ha, gradual (20%), south-facing slope at 1,000 m elevation. Mean annual temperature was 10 °C and mean annual precipitation was 180 cm. Soils were a Cullasaja–Tuckasegee complex, fine-loamy to loamy-skeletal, mixed, mesic Typic Haplumbrepts (Thomas 1996). Dominant overstory species were *Acer rubrum*, *Quercus prinus*, *Liriodendron tulipifera*, *Quercus rubra*, and *Carya* spp.

METHODS

Prescribed Burn

In April 1998, the area was prescription burned by a hand-lit backing fire. The backfire was started at the top of the slope. Strip headfires were then set across the slope at approximately 4-m intervals. The headfires burned across the slope and continued uphill to meet the backing fire. A raked fire line at the drainage below the slope, a Forest Service road, and an adjacent burned area to the north contained the fire. Air temperatures ranged from 8 to 18 °C for the duration of the fire prescription (1000 to 1500 EST). Relative humidity ranged between 40% and 30%, decreasing as the afternoon progressed. Flame lengths were between 30 and 60 cm.

Sampling

In March 1998, 1 month before the burn, we established plots along three parallel, approximately east–west transects (260 °W). To quantify combustion temperature at each plot, we used heat-sensitive paint (Omega Engineering, Inc., Stamford, CT) applied to ceramic tiles (10 cm × 20 cm). One to two days prior to burning, tiles were suspended with metal conduit at 30 cm aboveground on the north and south of each transect line. Heat sensitivities of the paint ranged from 52 to 804 °C, at increments of approximately 20 °C between 52 and 400 °C, and 100 °C between 400 and 804 °C.

Prior to burning, we sampled forest floor components using 20 0.09-m^2 quadrats/transect, randomly located at either 1 m north or south of each transect line ($n = 60$ samples). Before the burn, we established post-burn sample locations within 1 m of the pre-burn samples and marked quadrat corners with a metal pin flag. Post-burn quadrats were co-located with the temperature tiles. Material within the quadrat was separated into three components: small wood <7.5-cm diameter, litter (Oi), and a combined fermentation and humus component (Oe + Oa). A 0.3 × 0.3-m wooden sampling frame was used to define the sampling area. Small wood (<7.5-cm diameter) within the sampling frame was cut using pruning shears, and forest floor was removed by component (i.e., Oi, Oe + Oa) after cutting along the inside of the sampling frame with a knife. Forest floor materials were placed in a paper bag and transported to the laboratory where they were dried for at least 72 h at 60 °C and weighed. Within 1 week after burning, the post-burn forest floor quadrats were sampled using the same procedures. Carbon and nitrogen concentrations of forest floor components were determined on ground samples using a Perkin-Elmer 2400 CHN Elemental Analyzer (Norwalk, CT).

Using the methods of W. Jarrell (Soil Water and Water Quality, Inc. [Portland, OR], personal communication), we estimated effects of burning on soil nutrient availability with anion and cation exchange resin membrane sheets. Both cation and anion resin sheets were prepared for placement in the soil by repeated washing (3 times for 10 min each) in 0.5-M $NaHCO_3$ solution to charge all exchange sites. Resin sheets were placed at all plots along the vegetation sampling transect within 1 m of the temperature tiles (80 cation and 80 anion sheets) 1 day before the prescribed burn. Additional sheets were placed about 3 m outside the prescribed burn area (16 cation and 16 anion sheets) to be used as controls. Sheets were placed 5 cm below the surface of the mineral soil using a 5-cm-diameter bulb planter. Resin sheets were left in place for 11 days after prescribed burning (12 days total). Exchangeable soil nutrient availability was measured again in April 1999 using the same procedures. Sheets from both burned and control areas were removed from the soil, and excess soil and organic matter were gently scraped from the resin sheet surface before placing in one zipper-type plastic bag per sample location. Within 24 h, sheets were rinsed thoroughly with deionized water to remove any remaining soil and organic matter particles, and adsorbed nutrients were extracted from the sheets. Each pair of resin sheets (anion and cation) from each sample plot were placed in a 10-cm petri dish with 25 ml of 0.5-M HCl and shaken gently for 20 h. Solutions were analyzed for NO_3–N, PO_4, and NH_4–N, using a Perstorp autoanalyzer. A Perkin-Elmer atomic absorption spectrophotometer was used to determine Ca, K, and Mg concentrations in solution. All values are presented as µg/cm^2 of resin sheet surface area.

Along each transect, we inventoried woody vegetation in five 10 × 10-m plots. The vegetation was measured by layers: the overstory layer (10 × 10-m plots) included all trees ≥2.5 cm diameter at breast height (DBH; 1.37 m above ground); and the understory layer (nested 5 × 5-m subplots) included all woody stems <2.5 cm DBH and diameter was measured at 3 cm above ground level (basal diameter). All woody stems were measured to the nearest 0.1 cm and recorded by

Table 1. Forest floor mass, carbon, and nitrogen pools before (pre-burn 1998) and after prescribed fire (post-burn 1998) in the Nantahala National Forest, North Carolina.

	Litter (Oi)		Fermentation + humus (Oe + Oa)		Small wood (<7.5 cm diameter)	
Forest floor	Pre-burn 1998	Post-burn 1998	Pre-burn 1998	Post-burn 1998	Pre-burn 1998	Post-burn 1998
Nitrogen concentration (%)	1.04 (0.01)A[a]	1.35 (0.08)B	1.38 (0.03)A	1.20 (0.04)B	0.66 (0.02)A	0.74 (0.05)A
Carbon concentration (%)	48.2 (0.14)A	47.5 (0.45)A	43.4 (0.6)A	37.5 (1.2)B	47.2 (0.14)A	51.1 (0.42)B
C/N ratio	46.7 (0.7)A	42.6 (2.1)A	32.0 (0.6)A	32.0 (0.7)A	77.7 (3.3)A	101.4 (11.6)A
Nitrogen (kg/ha)	45.8 (2.5)A	3.9 (0.8)B	63.3 (6.3)A	27.6 (3.3)B	27.4 (3.4)A	14.3 (4.4)B
Percent nitrogen loss		91.5		56.4		47.8
Carbon (kg/ha)	2114.9 (111.4)A	156.5 (35.3)B	1933.5 (174.8)A	895.7 (124.3)B	2107.0 (274.9)A	1432.5 (417.1)A
Percent carbon loss		92.6		53.7		32.0
Mass (kg/ha)	4381.0 (228.5)A	336.0 (75.4)B	4439.6 (403.4)A	2292.7 (279.5)B	4480.1 (583.2)A	2846.5 (823.6)B
Percent mass loss		92.3		48.4		36.5

[a] Different letters indicate significant ($P \le 0.05$) differences between pre-burn and post-burn levels. Standard errors are in parentheses.

Table 2. Average values (standard errors) for available soil nutrients (μg/cm^2) immediately after burning (post-burn 1998) and 1 year after burning (post-burn 1999) for the Mulberry prescribed understory burn, western North Carolina.

	Post-burn 1998		Post-burn 1999	
Nutrient	Control	Burn	Control	Burn
NO_3^-	0.330 (0.076)	0.738 (0.071)	0.506 (0.110)	0.753 (0.083)
NH_4^+	1.251 (0.574)	4.369 (0.472)	0.554 (0.205)	0.672 (0.116)
PO_4^-	0.015 (0.004)	0.033 (0.007)	0.047 (0.007)	0.062 (0.009)
Ca^{++}	20.40 (1.96)	62.17 (5.29)	14.68 (1.87)	17.65 (1.34)
Mg^{++}	7.32 (0.49)	20.24 (1.52)	6.48 (1.03)	6.36 (0.36)
K^+	26.91 (4.20)	36.81 (3.77)	10.79 (1.16)	12.02 (0.73)

species. In the 5 × 5-m understory plots, seedlings and saplings of *Quercus* spp., *Carya* spp., *Acer rubrum*, *Nyssa sylvatica*, *Liriodendron tulipifera*, *Magnolia acuminata*, *Robinia pseudoacacia*, and *Oxydendrum arboreum* were tagged, and height and basal diameter were measured on these individuals. In July 1998, after the burn, we measured all of the plots in the same manner as the pre-burn inventory.

Statistical Analyses

We used analysis of variance to test for difference between pre-burn and post-burn forest floor, C and N pools, and understory density and basal area (PROC GLM; SAS Institute 2000). We used a two-factor analysis of variance (PROC GLM; SAS Institute 2000) to test for significant effects of treatment (control, burn) and year (1998, 1999) on soil nutrient availability.

RESULTS

Fire Intensity and Forest Floor Mass, Carbon, and Nitrogen Pools and Losses

Based on the temperature tile readings, fire intensity ranged from 66 to 800 °C with an average of 188 °C (SE = 12.7, $n = 60$) across the burned area. Across the site, burning significantly reduced forest floor mass, C, and N (Table 1). Forest floor mass loss was 92% in the litter (Oi), 48% in the fermentation + humus (Oe + Oa), and 36% in the small wood fraction. Forest floor carbon loss was 93% in the Oi, 54% in the Oe + Oa, and 32% in the small wood fraction. The forest floor nitrogen pool was substantially reduced after burning: by 92% in the Oi, 56% in the Oe + Oa, and 48% in the small wood fraction (Table 1). In terms of C and N concentration changes, N concentration was significantly higher in the Oi layer, and C and N concentration were significantly lower in the Oe + Oa layer after burning (Table 1).

As expected, locations experiencing higher flame temperatures also had higher Oi mass loss (temperature vs. Oi mass loss: $R = 0.640$, $P = 0.010$), Oi C loss (temperature vs. Oi C loss: $R = 0.625$, $P = 0.013$), Oi N loss (temperature vs. Oi N loss: $R = 0.513$, $P = 0.050$), and small wood mass loss (temperature vs. small wood loss: $R = 0.520$, $P = 0.047$). However, we detected no significant relationships between flame temperature and Oe + Oa mass loss.

Available Soil Nutrients

Prescribed burning resulted in the release of available soil nutrients. Nitrate, NH_4, Ca, and Mg were significantly greater in the burned area compared with the adjacent control after burning (Tables 2 and 3). Immediately after burning, NO_3 was more than twice as high, NH_4 was 4 times higher, and Ca and Mg were 3 times higher on the burned plots than on the control plots. One year after burning, NH_4, Ca, and Mg levels were no longer significantly different between burned and control plots. Although there appeared to be a significant increase in available PO_4 and a decrease in available K between years 1998 and 1999, available PO_4 and K were not significantly changed due to understory burning in either year (i.e., no significant treatment effect) (Table 3). While there were significant differences between years for most nutrients (NH_4, Ca, K, Mg, and PO_4), NO_3 was the only nutrient to remain significantly higher on the burned than the control area 1 year after burning.

Vegetation Dynamics

Overstory

Before burning, *A. rubrum*, *C. florida*, *O. arboreum*, *L. tulipifera*, *Q. prinus*, and *Carya* spp. had the highest density in the overstory (Table 4). Fifty-eight percent of the overstory trees were killed by the fire.

Table 3. Analysis of variance table for available soil nutrients post-burn (1998) and post-burn (1999) in the Nantahala National Forest, North Carolina.

Dependent variable	Source	Mean square	*F*	*P*
NO_3^-	Year	0.1857	0.60	0.4415
	Treatment	2.1916	7.03	0.0089
	Year × Treatment	0.1319	0.42	0.5164
NH_4^+	Year	98.5	15.54	0.0001
	Treatment	53.4	8.43	0.0043
	Year × Treatment	45.9	7.24	0.0080
PO_4^-	Year	0.0194	5.51	0.0203
	Treatment	0.0055	1.56	0.2136
	Year × Treatment	0.00002	0.01	0.9293
Ca^{++}	Year	12866	17.56	0.0001
	Treatment	10204	13.92	0.0003
	Year × Treatment	7679	10.48	0.0015
Mg^{++}	Year	1104	18.31	0.0001
	Treatment	835	13.85	0.0003
	Year × Treatment	868	14.39	0.0002
K^+	Year	8532	21.95	0.0001
	Treatment	632	1.63	0.2043
	Year × Treatment	383	0.98	0.3227

However, most of this mortality was trees in the smaller size class (<10.0 cm DBH) (Figure 1). Consequently, overstory basal area was only reduced by 18% (Table 4). The highest percent mortality occurred for *C. florida* and *A. rubrum* followed by *N. sylvatica* and *O. arboreum* (Table 5). Overstory basal area was reduced by 51% for *A. rubrum*, but was only reduced by 4% for *Carya* spp., 2% for *L. tulipifera*, 2% for *Q. prinus*, and 6% for *Q. rubra*. Some species with low densities and small size such as *Amelanchier arborea*, *Betula lenta*, *Castanea dentata*, *M. acuminata*, *Rhododendron calendulaceum*, and *Sassafras albidum* had no living stems in the overstory layer after burning (Table 4). Due to the difference in percent mortality among species, proportional basal area composition shifted. Before burning, *Quercus* spp. (*Q. prinus*, *Q. rubra*, and *Q. velutina*) composed 37% of the total basal area, *A. rubrum* composed 24%, *L. tulipifera*

Table 4. Overstory density (stems/ha) and basal area (m^2/ha) before burning (pre-burn 1998) and the first growing season after burning (post-burn 1998) in Nantahala National Forest, North Carolina.

	Pre-burn 1998		Post-burn 1998	
Species	Density	Basal area	Density	Basal area
Acer rubrum	453	7.967	160	4.099
Amelanchier arborea	40	0.372		
Betula lenta	7	0.053		
Carya spp.	87	2.831	53	2.728
Castanea dentata	20	0.019		
Cornus florida	187	0.998	27	0.274
Fraxinus americana	7	0.006	7	0.006
Kalmia latifolia	20	0.020	7	0.012
Liriodendron tulipifera	107	5.923	80	5.801
Magnolia acuminata	7	0.014		
Nyssa sylvatica	73	0.363	33	0.268
Oxydendrum arboreum	180	2.572	100	2.165
Quercus prinus	87	6.278	60	6.124
Quercus rubra	40	3.783	20	3.558
Quercus velutina	27	2.256	27	2.256
Rhododendron calendulaceum	7	0.006		
Sassafras albidum	7	0.012		
Total	1356	33.47	574	27.29

composed 18%, and *Carya* spp. composed 8%. After burning, *Quercus* spp. increased proportionately to 44% of the total basal area, *A. rubrum* decreased to 15%, and *L. tulipifera* (21%) and *Carya* spp. (10%) increased slightly (Table 4).

Understory

Percent mortality of understory stems also varied among species (Table 5). A higher percentage of stems of *A. rubrum* did not resprout after burning than any other species. *Pinus strobus* and *Tsuga canadensis*, both in low frequency and abundance before burning, were no longer present in the understory layer after burning (Table 6). *Carya* spp. increased in both frequency and density after burning.

Understory density increased by 6 times after burning, whereas basal area stayed about the same (Table 6). Before burning, 6 of the 28 understory species composed 66% of the total density and 53% of the basal area. Species ranked by density were *Pyrularia pubera* > *Vaccinium* spp. > *A. rubrum* > *A. arborea* > *Gaylussacia baccata* > *S. albidum*. In post-burn 1998, 6 of the 26 species comprised 81% of the total density and 69% of the basal area. Species ranked by density were *L. tulipifera* > *Vitis* spp. > *R. pseudoacacia* > *P. pubera* > *Vaccinium* spp. > *A. rubrum*. In post-burn 1999, 6 of the 26 species present composed 66% of the total density and 63% of the basal area. Species ranked by density were *L. tulipifera* > *Vaccinium* spp. > *P. pubera* > *Vitis* spp. > *Rubus* spp. > *A. rubrum* (Table 6).

The first growing season after burning (1998), *L. tulipifera* had high recruitment with most of those recruits from seed germination (Table 7). However, the majority of those new seedlings died by the 1999 growing season, but another flush of seed germination resulted in approximately 19,000 seedlings/ha in 1999. *R. pseudoacacia* had the second highest number of new seedlings in 1998 (Table 7). By 1999, *R. pseudoacacia* ranked 7th based on density; 52% of these stems were survivors from the 1998 growing season and an additional 48% were from new seedling recruitment in 1999 (Table 7). In contrast, *A. rubrum*, which ranked 6th based on density, primarily regenerated from stem sprouts in 1998. Forty percent of the stem recruitment originated from burned understory stems, while 49% originated from overstory trees killed by the fire (Table 7). Of the oaks, *Q. rubra* had the highest amount of new seedling recruitment. Over 3,000 seedlings/ha emerged after burning in 1998, approximately 70% survived into 1999, while an additional 1,200 seedlings/ha emerged in 1999. *Q. velutina* also had high recruitment and survivorship with the majority of its recruits from seed germination (Table 7).

DISCUSSION

Paleoecological results from Horse Cove Bog in western North Carolina indicate that selective use of fire by Native Americans during the last 4,000 years played an important role in determining the composition of southern Appalachian vegetation (Delcourt and Delcourt 1997). Following European settlement, disturbance regimes, particularly selective logging, fire suppression and chestnut blight, have altered forest composition and structure during the past century

Table 5. Frequency of occurrence (%) and mortality (%) of understory (stems <2.5 cm diameter at breast height) and overstory (stems ≥2.5 cm diameter at breast height) tree species at Mulberry prescribed burn site, western North Carolina, 1998–1999.

	Understory		Overstory	
Species	Frequency	Mortality[a,b]	Frequency	Mortality[b]
Acer rubrum	93	87 (6.0)	100	65.4 (8.1)
Carya spp.	60	38 (6.7)	60	35.2 (14.8)
Cornus florida			93	81.0 (10.3)
Liriodendron tulipifera	40	67 (11.4)	60	22.2 (12.4)
Nyssa sylvatica	60	53 (13.8)	33	53.3 (16.2)
Oxydendrum arboreum	13	0	60	45.4 (8.9)
Quercus alba	7	0	0	0
Quercus prinus	80	64 (11.4)	53	37.5 (15.7)
Quercus rubra	87	59 (10.3)	33	40.0 (24.5)
Quercus velutina	40	17 (16.7)	13	0
Robinia pseudoacacia	13	0	0	0

[a] Mortality for understory trees is the percentage of tagged stems that did not sprout after burning (post-burn 1998); all aboveground stems were burned. Average mortality was calculated based on plots only where the species occurred.

[b] Standard errors are in parentheses.

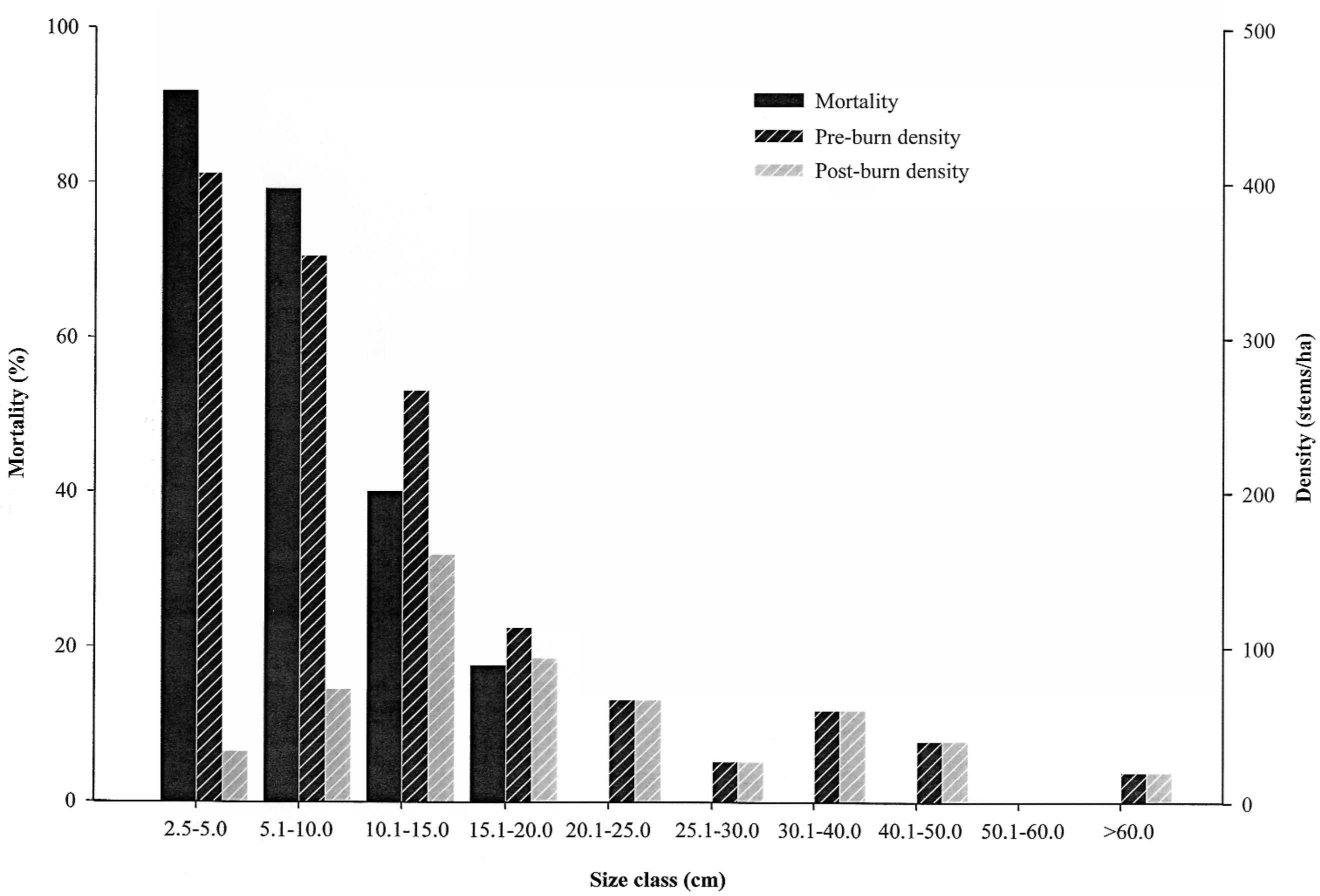

Figure 1. Size-class distribution, mortality, and density of overstory stems before burning (March 1998) and after burning (July 1998) in the Nantahala National Forest, North Carolina.

(Abrams 2000, Lorimer 2001). Reintroduction of fire into the current forests of the southern Appalachians will have various effects on ecosystem properties and vegetation structure and composition depending on several factors including fire type (intensity, frequency, timing, and scale) and community type (current species composition and structure, slope, soils, microclimate, and fuel load).

Single, dormant-season fires, such as those applied in this study, may consume a large proportion of the forest floor and change the apparent character of the surface organic matter complex without having major effects on soil enzyme activity (Boerner et al. 2000*a*). High-intensity fires that consume most of the forest floor can reduce soil organic matter and nutrient content, whereas low-intensity fires typically burn unconsolidated litter and fine woody fuels and usually have little impact on soil organic matter and nutrient content (Boerner et al. 2000*b*). In our study, the low- to moderate-intensity fire consumed a large proportion of the Oi layer and about half of the Oe + Oa layer. Although the fire consumed a larger percentage of the Oe + Oa layer than reported in other studies in the southern Appalachians (Vose and Swank 1993, Vose et al. 1999), the absolute amount of this layer consumed was similar (2,160 kg/ha [Vose et al. 1999] vs. 2,293 kg/ha [this study]). In this mesic mixed-oak forest, the total forest floor mass ([Oi + Oe] + Oa ≅ 8.8 Mg/ha) was much less than that on drier pine–hardwood sites ([Oi + Oe] + Oa mass ≅ 30 Mg/ha [Vose and Swank 1993, Vose et al. 1999]) where decomposition rates are slower. An intact forest floor is important for maintaining soil stability and for providing a nutrient reservoir. In terms of N losses, approximately 90 kg/ha of forest floor N was lost from the site due to forest floor consumption. This loss is 4-fold less than observed in other studies in mixed pine–hardwood ecosystems (Vose and Swank 1993) and represents a very small percentage of total ecosystem N (Knoepp and Swank 1997). For example, Vose and Swank (1993) reported average total aboveground N loss of 350 kg/ha for three pine–hardwood ecosystems. Taken across sites, N losses from burning represented about 20% of the total soil N pool to a 20-cm depth (Knoepp and Swank 1993) .

Table 6. Frequency of occurrence (%) and average density (stems/ha) and basal area (m^2/ha) of all woody understory species (<2.5 cm diameter at breast height) before burning (pre-burn 1998) and the first (post-burn 1998) and second (post-burn 1999) growing seasons after burning in the Nantahala National Forest, North Carolina.

	Pre-burn 1998			Post-burn 1998			Post-burn 1999		
Species	Frequency	Density	Basal area	Frequency	Density	Basal area	Frequency	Density	Basal area
Acer pensylvanicum	20	400	0.053	33	827	0.014	20	747	0.031
Acer rubrum	100	3253	0.175	100	11440	0.185	93	9653	0.373
Amelanchier arborea	93	2720	0.066	93	2747	0.014	100	3493	0.039
Calycanthus floridus	7	80	0.001						
Carya spp.	67	987	0.048	93	2293	0.025	100	2453	0.053
Castanea dentata	60	1147	0.093	60	1067	0.023	53	933	0.060
Castanea pumila	7	53	0.002				7	53	<0.001
Ceanothus americanus				7	107	<0.001			
Cornus florida	47	480	0.055	47	1440	0.005	33	1280	0.022
Fagus grandifolia	13	53	0.010	7	53	<0.001	7	53	<0.001
Gaylussacia baccata	27	1787	0.019				7	2560	0.006
Kalmia latifolia	13	133	0.020				7	400	0.002
Liriodendron tulipifera	60	1307	0.070	100	75440	0.222	93	20880	0.140
Magnolia acuminata				7	133	0.009	7	187	0.028
Nyssa sylvatica	67	1573	0.063	73	3280	0.053	73	3467	0.104
Oxydendrum arboreum	20	160	0.019	40	1067	0.020	40	1440	0.064
Parthenocissus quinquefolia				40	7760	0.024			
Pinus strobus	20	53	0.004						
Prunus serotina							7	27	<0.001
Pyrularia pubera	67	9893	0.317	67	15306	0.197	60	16613	0.342
Quercus alba	7	293	0.006	13	773	0.003	20	1173	0.010
Quercus prinus	87	1200	0.024	73	1680	0.026	60	1840	0.046
Quercus rubra	87	1467	0.028	80	4880	0.026	80	5013	0.038
Quercus velutina	40	320	0.005	93	2960	0.015	80	2560	0.021
Rhododendron calendulaceum	7	240	0.031	7	720	0.007	13	1440	0.019
Rhus glabra							13	53	<0.001
Robinia pseudoacacia	13	53	0.003	93	15707	0.060	93	9600	0.198
Rubus spp.	13	1147	0.034	33	7760	0.090	60	12560	0.441
Sassafras albidum	80	1520	0.028	93	7333	0.037	100	7600	0.070
Symplocos tinctoria	20	160	0.002	27	427	0.003	47	667	0.006
Tsuga canadensis	7	27	<0.001						
Vaccinium spp.	40	4853	0.031	33	14346	0.046	47	17040	0.044
Viburnum acerifolium				20	1040	0.004	27	667	0.005
Vitis spp.	47	827	0.063	100	37733	0.140	100	15147	0.044
Total		36187 (4914)[a]	1.270 (0.199)[a]		210560 (30887)[a]	1.224 (0.195)[a]		139600 (22880)[a]	2.207 (0.513)[a]

[a] Standard errors are in parentheses.

Generally, prescribed fires increase soil exchangeable nutrient pools (Reich et al. 1990, Knoepp and Swank 1993, Neary et al. 2000); however, results can vary depending on fire severity and duration. Transient increases in nutrient availability may occur immediately after a prescribed burn (Boerner et al. 1988). In our study, the prescribed fire and subsequent mass consumption had only a short-term effect on most soil nutrients. By the second growing season after the fire, with the exception of NO_3^-, exchangeable soil nutrients had returned to control levels. However, the transient increases in nutrient supply produced by prescribed burning may contribute to the abundant regeneration and rapid regrowth of understory woody species.

The structure and composition of this mesic mixed-oak forest were significantly altered by this single

Table 7. Recruitment and survival (stems/ha) of select understory trees the first (post-burn 1998) and second (post-burn 1999) growing seasons after burning in the Nantahala National Forest, National Carolina.

	Recruitment post-burn 1998				Recruitment post-burn 1999						
Species	Number of sprouts from original stems	Number of new sprouts[a]	Seedlings	Total recruitment in 1998	Number of new sprouts[a]	Seedlings	Total recruitment in 1999	Number of stems surviving from originals	Number of stems surviving from 1998	Survivors (originals + 1998)	Total regeneration (1999 recruitment + survivors)
Acer rubrum	4640	5627	640 (533)[b]	11440	293	1040	1333	4186	4133	8319	9652
Carya spp.	1093	427	773	2293	80	373	453	880	1120	2000	2453
Liriodendron tulipifera	1120	53	1014 (73253)[b]	75440	0	880 (18134)[b]	19014	1173	693	1866	20880
Nyssa sylvatica	1120	1467	666 (27)[b]	3280	0	746	746	1067	1653	2720	3466
Oxydendrum arboreum	480	560	27	1067	293	0	293	480	667	1147	1440
Quercus alba	507	187	40	734	240	133	373	507	293	800	1173
Quercus prinus	773	613	294	1680	107	159	266	800	773	1573	1839
Quercus rubra	1147	613	2854 (268)[b]	4880	266	1200	1466	907	2640	3547	5013
Quercus velutina	613	480	1867	2960	0	533	533	480	1546	2026	2559
Robinia pseudoacacia	107	160	7386 (8053)[b]	15706	0	4586	4586	54	4960	5014	9600

[a] Multiple stem clumps or sprouts from dead overstory trees.

[b] New seedling germinants (<5.0 cm height) not tagged.

understory burn. Similar to findings by others in mesic hardwood forests (Reich et al. 1990, Kruger and Reich 1997, Blake and Schuette 2000, Peterson and Reich 2001), we found that understory burning had an impact on the most fire-sensitive species such as *A. rubrum*, *N. sylvatica*, and *C. florida*. In contrast, *L. tulipifera*, considered a fire-intolerant species, had lower percent mortality than other tree species. Most of its stems were in the larger size class (>20 cm DBH) and were not affected by this low-intensity, moderate-severity fire. *A. rubrum* will probably remain an overstory dominant. Although this species experienced high mortality, it still has the highest density and the third highest basal area in the overstory. Size-class distribution of overstory trees was also changed after burning. Greater mortality in the small diameter individuals changed the distribution of the size class from a reverse J-shaped size distribution, with the highest stem densities in the 2.5- to 10-cm size class before burning to a unimodal size distribution after burning, with highest stem densities in the 10- to 20-cm size class.

Regeneration success and mode of reproduction were variable among the tree species sampled (i.e., tagged individuals). *A. rubrum*, *L. tulipifera*, and *R. pseudoacacia* had high regeneration success following the fire. *A. rubrum* recruitment was primarily from stem sprouting, whereas *L. tulipifera* recruitment was primarily from seed germination. *R. pseudoacacia*, a minor understory species before burning, was the third most abundant tree species after burning. Most *R. pseudoacacia* recruitment was probably contributed by root sprouts rather than seed germination because this species sprouts prolifically from existing root systems after disturbance (Boring et al. 1981); however, we did not trace the root systems to determine the origin of individuals for this species.

The significant recruitment of *Quercus* spp. (*Q. alba*, *Q. prinus*, *Q. rubra*, and *Q. velutina*) through both seedlings and sprouts suggests that *Quercus* spp. may become overstory dominants. *Quercus* spp. are more shade-tolerant than either *L. tulipifera* or *R. pseudoacacia*, the other species with significant recruitment. *L. tulipifera* and *R. pseudoacacia* both grow rapidly under high light conditions and can become the dominant overstory species in heavily disturbed ecosystems in the southern Appalachians (Phillips and Shure 1990, Elliott et al. 1997, Elliott et al. 1998). However, the presence of a partial canopy of live trees in this low-intensity understory burn may provide too much shade for *L. tulipifera* and *R. pseudoacacia* to survive and grow into the canopy, whereas the more shade-tolerant *Quercus* spp. may be able to thrive in this partial shade (Loftis and McGee 1993).

Relative to other hardwoods, fire should favor *Quercus* because of its thick bark, sprouting ability, resistance to rotting after scarring, and the suitability of fire-created seedbeds for acorn germination (Abrams 1996). In a study of post-fire community dynamics in a mesic hardwood forest (Kruger and Reich 1997), spring burning had little effect on the survival and height growth of northern red oak regeneration, but it decreased the density and growth rate of key hardwood competitors. In our study, the prolific regeneration of *A. rubrum*, a shade-tolerant species, suggests that a second understory fire may be necessary to reduce *A. rubrum* establishment and its potential competition with *Quercus* regeneration. Repeated fires in oak forests have been shown to significantly reduce the number of seedlings and saplings of *A. rubrum* and other shade-tolerant species (Kruger and Reich 1997, Arthur et al. 1998, Barnes and Van Lear 1998, Van Lear et al. 2000).

MANAGEMENT IMPLICATIONS

Moderate-intensity understory burning may be a useful tool to restore mesic mixed-oak communities in the southern Appalachians. Reintroduction of fire into these ecosystems may be beneficial by increasing soil nutrient availability, promoting *Quercus* regeneration and survival, increasing diversity of understory species, and reducing abundance of shade-tolerant and fire-intolerant species such as *A. rubrum*. We found short-term increases in soil nutrient availability without detrimental effects on forest floor mass or nutrient pools. The transient increases in exchangeable soil nutrients produced by prescribed burning may contribute to the abundant regeneration and rapid regrowth of understory woody species. In addition, the loss of forest floor N was less than observed in mixed pine–hardwood ecosystems. This N loss represents a very small percentage of total ecosystem N, suggesting little long-term impact on site N capital and productivity. The low- to moderate-intensity understory fire showed potential for reducing dominance of fire-sensitive species and increasing dominance of oaks. However, further reduction in fire-intolerant species such as *A. rubrum* may require repeated burning. While repeated burning may be beneficial for *Quercus* canopy recruitment, more research would be necessary to evaluate the effects of repeated burning on ecosystem processes, particularly total ecosystem C and N losses.

ACKNOWLEDGMENTS

This project was funded by the U.S. Department of Agriculture, Forest Service, Coweeta Hydrologic Laboratory in cooperation with the Wayah Ranger District of the Nantahala National Forest. We thank M.L. Wilkins, District Ranger, for his cooperation and assistance.

We also thank P. Clinton, L.C. Phillips, C. Sobek, and N. Stover for their assistance in data collection.

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