Site preparation burning to improve southern Appalachian pine-hardwood stands: aboveground biomass, forest floor mass, and nitrogen and carbon pools[1]

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On three sites in the southern Appalachians, stands characterized by sparse overstories and dense *Kalmia latifolia* L. shrub layers were felled in early summer and burned in early fall. Amounts of aboveground vegetation and forest floor mass, nitrogen (N), and carbon (C) were measured before and after treatment by sampling wood, foliage, herbs, grasses, and forest floor (Oi and Oe + Oa layers). Burning decreased woody mass by 48 to 60% across the three sites. The most intense burn reduced mass from 180 to 70 $Mg \cdot ha^{-1}$, and N and C losses were 300 $kg \cdot ha^{-1}$ and 52 $Mg \cdot ha^{-1}$, respectively. Significant losses of mass, N, and C occurred in the Oi layer, but not in the Oe + Oa layer. Foliage, herbs, and grasses were totally consumed by the fires. Total aboveground N losses across sites ranged from 193 to 480 $kg \cdot ha^{-1}$. These losses may be significant because N availability is low on these sites. Variations in patterns of mass, N, and C consumption were related to differences in amounts, types, size distributions, and moisture contents of fuels.

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Les peuplements situés sur trois stations dans la partie sud des Appalaches et caractérisés par un étage dominant clairsemé et une vegetation arbustive dense composée principalement de *Kalmia latifolia* L. ont été coupes au debut de l'été et brûlés au debut de I'automne. La quantité de vegetation aérienne ainsi que le poids de la couverture morte, de l'azote (N) et du carbone (C) ont été mesurés avant et après le traitement en Cchantillonnant le bois, le feuillage, les herbacées, les graminées et la couverture morte (horizons Oi et Oe + Oa). Le brfilage a réduit la masse ligneuse de 48 à 60% dans les trois stations. Le brfilage le plus intense a réduit la masse de 180 à 70 $Mg \cdot ha^{-1}$ et les pertes de N et de C atteignaient respectivement 300 $kg \cdot ha^{-1}$ et 52 $Mg \cdot ha^{-1}$. Des pertes importantes de masse, de N et de C sont survenues dans l'horizon Oi mais non dans l'horizon Oe + Oa. Le feuillage, les herbactes et les graminées ont été entièrement consumes par le feu. Les pertes totales de N dans la vegetation aérienne des deux stations variaient de 193 à 480 $kg \cdot ha^{-1}$. Ces pertes ne sont probablement pas negligeables Ctant donnée la faible disponibilité de N dans ces stations. Les variations dans les patrons de consommation de la masse. de N et de C ttaient fonction des differences dans la quantité, le type, la distribution des dimensions et le contenu en humidité des combustibles.

[Traduit par la redaction]

Introduction

prescribed tire is currently used as a site preparation treatment in mixed pine-hardwood ecosystems of the southern Appalachians. Stands receiving this treatment typically consist of mixtures of pitch pine (*Pinus rigida* Mill.), scarlet oak (*Quercus coccinea* Muenchh.), chestnut oak (*Quercus prinus* L.), red maple (*Acer rubrum* L.), and dense understories dominated by mountain laurel (*Kalmia latifolia* L.). Abusive land practices such as high grading and grazing, in combination with drought-induced insect (southern pine beetle) infestations, have left the stands with sparse, low-diversity, and slow-growing overstories. To improve the overstory composition and productivity of these ecosystems, the silvicultural prescription involves cutting all woody vegetation in early summer, burning with a high-intensity but low-severity fire in late summer, and planting white pine (*Pinus strobus* L.) on a wide spacing (i.e., 4 x 4 m). Burning facilitates planting and reduces mountain laurel competition with the planted seedlings. The desired future condition of the overstory is a productive pine-hardwood mixture, with white pine, which is resistant to southern pine beetles, as the dominant pine. The impacts of these treatments on nutrient cycling, productivity, and vegetation diversity are unknown. To determine these impacts, a long-term, multi-investigator study was established (Swift et al. 1993). The present paper addresses treatment impacts on aboveground mass and associated nitrogen (N) and carbon (C) pools.

Nitrogen most commonly limits productivity in forest ecosystems (Vitousek et al. 1982). Hence, it is critical that management activities consider methods for maintaining ecosystem N reserves. Aboveground biomass (woody, foliar, and herbaceous) and the forest floor are important reservoirs of nutrients in pine-dominated ecosystems (Boemer 1982). These pools are dynamic and contribute to N and C recycling processes, but management activities such as harvesting and burning alter pool sizes and biogeochemical cycling rates. In most ecosystems, the majority of N in woody mass is unavailable in the short-term because it is tied up in living tissue and deadwood, which decomposes slowly. Release or loss of nutrients from these pools as a result of burning can be substantial. Foliar mass, N, and C pools are important because they turn over rapidly and are the primary aboveground input to the soil. In hardwood ecosystems of the southern Appalachians, release of N from the forest floor provides approximately 50% of the total available N (Monk and Day 1988). The amount of forest floor and the rate of mineralization often determine the availability of N in early successional forest ecosystems (Wells and Morris 1982; Vitousek and Matson 1985). Hence, understanding the impacts of burning on the forest floor is critical, particularly on nutrient-poor sites where losses from aboveground pools can meaningfully reduce productivity of plant communities (Raison 1980).

Mass, N, and C have three potential fates in fires: *(i)* being lost to the atmosphere via volatilization or ash convection;

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(ii) being deposited on site as ash; and (iii) remaining on site as partially burned material (Boemer 1982). In addition, a small amount of N (e.g., <10 kg · ha-') may be transferred downward into the soil (Covington et al. 1991; Knoepp and Swank 1993) after burning. The amount volatilized depends on fire temperature. Losses of N can be substantial because it volatilizes at relatively low temperatures (200°C) (Boemer 1982). The majority of base cations are lost through ash convection.

In this study, we evaluated the impacts of felling and burning on aboveground N, C, and biomass pools in three watershed ecosystems. Our objectives were to (i) estimate losses of mass, N, and C from aboveground pools (i.e., wood, foliage, herbaceous vegetation, and forest floor); (ii) identify key pools contributing to losses of N and C; and (iii) evaluate differences in mass, N, and C losses due to variation in pretreatment vegetation characteristics and variation in fire characteristics.

Methods

Site and burning treatment

Treatments were imposed on three sites that were paired with control watersheds in the Nantahala National Forest of western North Carolina. Treated watersheds averaged about 4 ha and adjacent controls, about 1 ha. Two sites, denoted as Jacob East (JE) and Jacob West (JW), were within 200 m of each other. The Devil Den (DD) site was located approximately 20 km from the JE and JW sites. Soils are in the Cowee-Evard complex, a fine loamy, mixed, mesic Typic Hapludult characterized by a clay-loam layer from 30 to 60 cm deep. Average slopes ranged from 35 to 50%. JE and DD had southwestern aspects and JW had a western aspect. Five 15 x 33 m plots were established on each treated watershed 1 year prior to treatment. Control watersheds were used for analyses of changes in microclimate and soil and soil water chemistry. Swift et al. (1993) and Knoepp and Swank (1993) described these methods and effects.

All three watersheds were burned in September 1990 with fires of high intensity and low severity (Ottmar and Vihnanek 1991). Fire intensity relates to the upward heat pulse (Ryan and Noste 1985) produced by the fire. Fire severity incorporates the downward heat pulse and, from a practical standpoint, determines the consumption of forest floor and heat penetration into the mineral soil (Van Lear and Waldrop 1988). Temperatures in the forest floor and mineral soil (i.e., severity) ranged from 45 to 60°C at 2.5 to 5 cm below the surface, and peak flame temperature (i.e., intensity) ranged from 625 to 803°C (Ottmar and Vihnanek 1991). Additional site descriptions and burning characterizations are given by Swift et al. (1993).

Woody biomass before burning

In the winter of 1989, all woody biomass in standing vegetation (living and dead) was estimated on each 15 x 33 m plot. Stems were tallied by species, and diameters at breast height (DBH) (1.4 m above ground) were measured with a diameter tape on stems >10.2 cm. Measurements of live stems were used to determine stand structural characteristics (Table 1). Data from both living and dead stems were included in woody biomass estiniates. For hardwoods, total-tree biomass (stem, branch, and bark) was predicted from DBH with the general allometric equation of Clark and Schroeder (1986). For pines, total-tree biomass was predicted with the allometric equation of Van Lear et al. (1986) for loblolly pine (***Pinus taeda*** L.). Species-specific equations were not available for the pine species present on our sites (primarily pitch pine), so we assumed that the loblolly pine equations were generally applicable to other southern pines. Stems ≤10.2 cm at 1.4 m were measured on a 3 x 3 m plot in a randomly selected corner of each 15 x 33 m plot. If there was a clear stem (i.e., no branches below 1.4 m), stem diameter was measured at 1.4 m with either a diameter tape or calipers, depending on the size of the stem. Otherwise, diameter was measured at the base of the stem (approximately 3 cm above ground level) with calipers. Mountain laurel was measured only at the base. Biomass of trees 110.2 cm measured at 1.4 m was estimated with the allometric equations of Phillips (1981). Mountain laurel biomass was estimated with McGinty's (1972) equations for plants with basal circumference ≥12 cm and with equations from Boring and Swank (1986) for stems <12 cm. This combination of equations was needed because McGinty's (1972) data set did not include mountain laurel stems <12 cm. For all woody plants less than 1 cm at the base, biomass was predicted using the equations for oak seedlings from Boring (1979). For woody plants ≥1 cm at base (excluding plants measured at 1.4 m), biomass was estimated with equations from Boring (1982).

Foliage biomass

In September 1990 (≈1 week prior to burning), foliage biomass of felled vegetation (i.e., foliage still attached to the branches) was determined on four 1 x 1 m plots randomly located within each 15 x 33 m plot. Foliage was separated from branches in the field and sorted by major species groups; i.e., red oak, white oak, maple, pine, mountain laurel, sourwood, and others. Biomass was determined after drying at 70°C to constant weight. Fires consumed all foliage, so sampling was not required after the bums.

Herbaceous vegetation biomass

Prior to burning in September 1990, herbaceous biomass was estimated on the 1 x 1 m plots used to determine foliage biomass. Herbaceous vegetation (sorted by grasses and forbs) was clipped at ground level, dried to constant weight at 70°C, and weighed. Fire consumed all herbaceous vegetation within the 1 x 1 m plots, so no sampling was required after the bums.

Forest floor mass

Forest floor mass was determined on a 0.30 x 0.30 m plot nested within each 1 x 1 m plot (n = 4 per 15 x 33 m plot; n = 20 per treatment watershed). Forest floor was sampled by cutting and removing the forest floor within a square sampling frame. The Oi (L-layer) and Oe + Oa (F + H layers) layers were sampled separately. Samples were dried at 70°C to a constant weight and weighed. Sampling was conducted prior to burning in September 1990. Within 2 weeks after burning, the forest floor was resampled using four 0.30 x 0.30 m plots located within 1 m of the prebum 1 x 1 m sample plots. Where possible, Oi and Oe + Oa layers were separated; however, in many cases, the fires consumed the Oi layer, leaving the ashes mixed with the Oe + Oa layers.

Woody mass after burning

Residual woody material was sampled using two (2 x 2 m) plots randomly located within each 15 x 33 m plot. All woody material was removed from the plot and weighed on a portable scale. Subsamples of woody material were taken for moisture content determination to convert field-measured weight to ovendry weight. Where possible, residual woody mass was identified by genus (and in some cases, species). High fire severity prevented reliable wood identification on JE. Identification therefore was limited to JW and DD.

Carbon and nitrogen

Wood and branch samples were randomly taken from felled red oak, white oak, pine, maple, sourwood, mountain laurel, and "others" from areas outside the plots in September 1990 to estimate the total N and C concentrations by species groups. Nitrogen and C concentrations were determined for foliage and herbage before burning and for the forest floor and woody biomass before and after burning. Samples were oven-dried at 70°C, ground, and analyzed for N and C with a Perkin-Elmer 20400 CHN elemental analyzer. No corrections were made for ash content.

Statistical analyses

Significant differences between pre- and post-bum mass, N, and C were determined with Student's t-tests at a significance level of 0.05. Homogeneity of variances was tested with a folded form F-statistic (SAS Institute Inc. 1987). When variances were not homogeneous,

TABLE 1. Summary of stand characteristics for the three study sites based on two stem-diameter categories

	Mean DBH (cm)	Basal area ($m^2 \cdot ha^{-1}$)		Density (no. I ha)	
Site	>10 cm	>10 cm	≤10 cm	>10 cm	110 cm
JW	19.2	16.2	18.0	472	20 617
JE	20.8	18.7	35.0	460	35 593
DD	15.2	9.5	34.1	452	50 370

TABLE 2. Prebum mass, N, and C content of wood and foliage by major species group and site

	JW			JE			DD		
	Mass	N	C	Mass	N	C	Mass	N	C
Wood >10 cm									
Red oak	51.8	109	24.1	30.8	80	14.3	21.5	41	9.9
White oak	34.9	63	17.1	42.8	77	20.2	4.3	14	2.0
Pine	20.6	23	10.0	52.2	94	25.5	19.5	47	9.5
Maple	0.7	1	0.3	4.7	8	2.2	1.0	3	0.5
Sourwood	5.4	13	2.5	6.1	17	2.9	1.2	4	0.6
Other	4.6	10	2.2	9.0	33	4.3	5.7	13	2.7
Wood 110 cm									
Red oak	1.3	3	0.6	<1	<1	<1	5.7	11	2.5
White oak	0	0	0	3.5	6	1.7	<1	<1	<1
Pine	<1	<1	<1	0	0	0	0	0	0
Mountain laurel	11.8	32	5.7	26.7	56	13.1	27.0	75	13.2
Maple	<1	<1	<1	0	0	0	0.7	2	0.3
Sourwood	<1	<1	<1	0	0	0	0	0	0
Other	14.6	33	6.7	4.6	18	2.2	1.2	3	0.5
Foliage									
Red oak	1556	26	742	334	7	159	496	8	235
White oak	197	4	93	40	1	15	87	2	41
Pine	255	2	123	972	10	475	211	2	102
Mountain laurel	841	8	409	1662	16	798	2743	24	1312
Maple	71	1	34	203	4	98	134	2	63
Sourwood	160	2	77	31	1	15	216	2	101
Other	345	6	160	75	1	35	620	8	289

NOTE: Wood mass and C are in Mg ha-; wood N is in kg. ha^{-1}, and foliage mass, N, and C are in $kg \cdot ha^{-1}$

an approximate r-test and Satterthwaite's approximation (SAS Institute Inc. 1987) for computing degrees of freedom were used.

Results

Stand structure

Although mid- and over-story trees were generally >80 years old (Swift et al. 1993), mean DBH was 20 cm or less, and basal area of this vegetation group ranged from 9.5 to 18.7 $m^2 \cdot ha^{-1}$ (Table 1). Basal area of stems ≤10 cm exceeded the overstory basal area by as much as 3-fold. Stem density of the mountain laurel dominated understory was 40- to 100-fold greater than that of the overstory.

Prebum vegetation mass, N, and C pools

Mass, N, and C of stems >10 cm occurred primarily in three species groups: red oak ***(Quercus coccinea, Quercus marilandica*** Muenchh., ***Quercus velutina*** Lam.), white oak ***(Quercus stellata*** Wang., ***Quercus prinus, Quercus alba*** L.), and pine (***Pinus rigida***, ***Pinus virginiana*** Mill., ***Pinus echinata*** Mill.) (Table 2). In small wood (≤10 cm DBH and mountain laurel), mass, N, and C pools were distributed primarily in mountain laurel at JE and DD and in mountain laurel and "other" species (primarily ***Castanea pumila*** (L.) Mill.) at JW. Mountain laurel was the most important species at JE and DD in terms of the total pools of foliage mass, N, and C, and it was the second most important species at JW (Table 2). The importance of mountain laurel foliage to overall mass and nutrient pools reflects its abundance in the understory.

Because of differences in the consumption of fuels based on vegetation size and type, the distribution of mass, N, and C is important for interpreting losses discussed later in this paper. Taken collectively, the distribution of mass was ranked as large wood (>10 cm DBH) > small wood (≤10 cm DBH) > mountain laurel > foliage for JW and as large wood > mountain laurel > small wood > foliage for JE and DD (Table 3). In terms of N, the distribution was ranked as large wood > foliage > small wood > mountain laurel for JW and as large wood > mountain laurel > foliage > small wood for JE and DD. For C, the distribution was ranked as large wood > small wood > mountain laurel > foliage for JW and as large wood > mountain laurel > small wood > foliage for JE and DD.

In terms of total aboveground pools, woody vegetation was the dominant form of mass and C across all sites, with 82% at JW and JE and 73% at DD (Table 3). Approximately half of the total aboveground N pool was distributed in woody

TABLE 3. Prebum and postburn mass (Mg ha^{-1}), N (kg · ha^{-1}), and C (Mg ha^{-1}) pools

Site	Component	Prebum			Postburn			Loss		
		Mass	N	C	Mass	N	C	Mass	N	C
JW	Wood >10 cm	118.0 (17.7)	219 (36.8)	56.2 (8.7)						
	Wood ≤10 cm	15.9 (7.1)	36 (16.5)	7.4 (3.3)	76.3* (20.2)	102.8* (40.8)	36.1* (9.7)	69.3	184	33.2
	Mountain laurel	11.8 (6.8)	32 (18.5)	5.7 (3.3)						
	Foliage	3.4 (0.7)	49.3 (8.2)	1.6 (0.3)	0	0	0	3.4	49.3	1.6
	Forest floor									
	Oi	10.8 (1.6)	101.9 (12.0)	5.7 (0.7)	0.7* (0.2)	8.6* (2.7)	0.3* (0.1)	10.1	93.3	4.7
	Oe + Oa	20.2 (6.1)	198.4 (63.4)	8.6 (3.0)	17.7 (5.5)	157.9 (63)	6.3 (2.7)	2.5	40.5	2.3
	Herbs	0.4 (0.3)	4.3 (2.7)	0.2 (0.1)	0	0	0	0.5	4.3	0.2
	Grass	<0.1 (<0.1)	0.05 (0.05)	<0.1 (<0.1)	0	0	0	<0.1	0.05	<0.1
	Sprouts	0.5 (0.2)	4.9 (2.1)	0.2 (0.1)	0	0	0	0.5	4.9	0.2
	Site total	180.9	646	85.0	94.7	269	42.7	86.3	376	42.2
JE	Wood >10 cm	145.7 (15.2)	309 (24.6)	69.4 (7.4)						
	Wood 110 cm	8.1 (4.1)	24 (12.6)	3.8 (1.9)	70.5* (18.7)	84.6* (22.5)	34.2* (9.1)	109.9	305	52.1
	Mountain laurel	26.7 (4.2)	56 (8.8)	13.1 (2.1)						
	Foliage	3.3 (0.6)	38.9 (8.6)	16 (0.3)	0	0	0	3.3	38.9	1.6
	Forest floor									
	Oi	12.6 (1.2)	101.7 (8.0)	5.9 (0.7)	0.8* (0.7)	5.3* (4.7)	0.4* (0.3)	11.8	96.4	5.5
	Oe + Oa	27.0 (4.9)	238.6 (37)	10.5 (2.6)	23.2 (6.6)	212 (60.6)	9.0 (3.3)	3.8	26.6	1.5
	Herbs	0.5 (0.1)	9.3 (2.0)	0.2 (0.1)	0	0	0	0.5	9.3	0.2
	Grass	0	0	0	0	0	0	0	0	0
	Sprouts	0.3 (0.1)	3.8 (1.7)	0.1 (0.1)	0	0	0	0.3	3.8	0.1
	Site total	224.2	781.4	104.7	94.5	302	43.6	129.7	480	61.2
DD	Wood >10 cm	53.1 (10.2)	121 (26.3)	25.1 (4.9)						
	Wood ≤10 cm	7.6 (5.0)	15.6 (9.3)	3.5 (2.3)	38.3* (14.6)	82.2* (30)	18.4* (6.6)	49.3	129.2	23.4
	Mountain laurel	27.0 (2.9)	74.8 (8.9)	13.2 (1.4)						
	Foliage	4.5 (0.4)	47.5 (4.7)	2.1 (0.2)	0	0	0	4.5	47.5	2.1
	Forest floor									
	Oi	9.5 (0.8)	82.5 (4.7)	4.4 (0.4)	3.4* (1.0)	36.2* (7.9)	1.3* (0.2)	6.0	46.3	3.1

TABLE 3 (concluded)

Site	Component	Prebum Mass	Prebum N	Prebum C	Postburn Mass	Postburn N	Postburn C	Loss Mass	Loss N	Loss C
	Oe + Oa	22.1 (3.0)	233 (38.8)	8.2 (1.7)	22.3 (5.5)	278 (74.6)	8.4 (2.3)	0.6	-45.0	-0.2
	Herbs	0.5 (0.3)	4.9 (3.0)	0.2 (0.1)	0	0	0	0.5	4.9	0.2
	Grass	<0.1 (<0. 1)	0.40 (0.3)	co.1 (<0.1)	0	0	0	<0.1	0.40	<0.1
	Sprouts	1.3 (0.4)	9.8 (2.4)	0.6 (0.2)	0	0	0	1.3	9.8	0.6
Site total		126.1	590	51.4	63.9	396	28.2	62.2	193	29.3

NOTE: Values in parentheses are standard errors of plot means.

*Significant differences ($p < 0.05$) between pre- and post-bum. Assoicated p-values: for woody mass, p = 0.0294, 0.0015, and 0.0470; for woody N, p = 0.0068, 0.0000, and 0.0262; for woody C, p = 0.0307, 0.0017, and 0.0438; for Oi layer mass, p = 0.0029, 0.000 01, and 0.0014; for Oi layer N, p = 0.0012, 0.000 01, and 0.0009; for Oi layer C, p = 0.0032, 0.0001, and 0.0001 for JW, JE, and DD, respectively.

vegetation. Herbaceous vegetation, grasses, and sprouts represented an insignificant fraction (<1%) of the total aboveground mass, N, and C pools (Table 3).

Prebum forest floor mass, N, and C pools

Across watersheds, mass in the Oi layer ranged from 9.4 to 12.6 $Mg \cdot ha^{-1}$ and mass in the Oe + Oa layer ranged from 20.2 to 27.0 $Mg \cdot ha^{-1}$ (Table 3). Nitrogen ranged from 83 to 102 $kg \cdot ha^{-1}$ in the Oi layer and from 198 to 239 $kg \cdot ha^{-1}$ in the Oe + Oa layer. Approximately half of the total N pool (aboveground vegetation + forest floor) was contained in the forest floor (Oi and Oe + Oa combined). Carbon ranged from 4.4 to 5.9 $Mg \cdot ha^{-1}$ in the Oi layer and from 8.2 to 10.5 $Mg \cdot ha^{-1}$ in the Oe + Oa layer.

Postburn mass, N, and C pools

On the watersheds, burning significantly reduced woody mass, N, and C (Table 3). For postburn estimates in Table 3, it was not possible to separate mountain laurel, >10 cm wood, or ≤10 cm wood, and thus, these classifications were combined. As a percent of pretreatment total, mass consumption was greatest on JE (109.9 $Mg \cdot ha^{-1}$, or 61% of prebum total), followed by DD (49.3 $Mg \cdot ha^{-1}$, or 56% of prebum total) and JW (69.3 $Mg \cdot ha^{-1}$, or 47% of preburn total). Nitrogen losses from woody material ranged from 129 to 305 $kg \cdot ha^{-1}$, and carbon losses ranged from 25.5 to 52.1 $Mg \cdot ha^{-1}$. On average, wood N concentration was higher before than after the burning (e.g., 0.23 vs. 0.13% N for JW; 0.24 vs. 0.12% N for JE, 0.24 vs. 0.21% N for DD). Possible causes include volatilization of N from partially burned wood and an increased representation of large wood, which characteristically had lower N concentration than small wood.

Mass, N, and C were significantly reduced in the Oi layer of the forest floor on all three watersheds (Table 3). Reduction was nearly complete on the JW and JE watersheds (>90%). On DD, mass, N, and C in the Oi layer were reduced to about 50% of their prebum levels. In contrast, although they were slightly lower after burning at the JE and JW watersheds, pools in the Oe + Oa layer were not significantly reduced at any of the watersheds. In terms of concentration changes in the forest floor, the only significant change was an increase in N in the Oi layer at JW, from a prebum level of 0.99% to a postburn level of 1.27% (Table 4). This may have been the result of a downward flux of volatilized N. While forest floor C/N ratios were consistently lower after burning, statistically significant differences occurred only for the Oi layer at the DD site.

Fires consumed all foliage, herbaceous vegetation, grasses. and sprouts (Table 3). Combined losses from this vegetation group ranged from 52 to 63 $kg \cdot ha^{-1}$.

Taken collectively, aboveground mass and C losses were approximately 48% of the prebum total on JW, 58% of the prebum total on JE, and 49% of the prebum total on DD (Table 3). Total N losses were 373 $kg \cdot ha^{-1}$ for JW, 480 $kg \cdot ha^{-1}$ for JE, and 193 $kg \cdot ha^{-1}$ for DD. These values represent losses of approximately 30% (DD) to 60% (JW and JE) of the total aboveground prebum N pools.

Discussion

Stand structure

The condition of the mixed pine-hardwood stands was poor (Table 1). The low mean diameter and density of overstory trees reflects the cumulative impacts of inherently low site quality, selective harvests of large trees, and insect-related mortality. In addition, the substantial density and basal area of the mountain laurel dominated understory and shrub layer emphasizes the shift in community structure from overstory to understory and shrub components. Changes in the vegetation structure and composition in stands 13 years after treatment are reported in Clinton et al. (1993).

Loss of mass, N, and C

Comparing our results with earlier findings is difficult because in other site preparation studies, sites were burned after overstory trees were removed. Comparison with prescribed burning studies is also difficult because stands are burned with the woody fuel standing. In our study, it was not economical to remove the few large (and typically low-quality) trees. Thus, losses of mass, N, and C from these sites were lower than would be expected because the large woody fuels were reduced the least after burning (Ottmar and Vihnanek 1991). After our bums, substantial proportions of the woody mass, N, and C were contained in the large material. Despite these differences, quantities and patterns of mass and N reduction are within the ranges reported for a variety of pine systems and types of bums.

In the most relevant comparisons, Danielovich (1986) reported a mass reduction of 32% for slash and felled resid-

TABLE 4. Forest floor pre- and post-bum N and C concentration (%), and C/N ratio (C weight / N weight) by layer and site

Site	Forest floor	Nutrient	Prebum	Postburn	t	df	$p > t$
JW	Oi	N	0.96 (0.04)	1.27 (0.08)	-3.4845	7.0	0.0102
		C	46.34 (0.80)	50.08 (2.00)	− 1.9427	7.0	0.0392
		C/N	49.58 (2.36)	39.83 (4.26)	2.1191	7.0	0.07 18
	Oa+Oe	N	0.95 (0.04)	0.84 (0.06)	1.4968	8.0	0.1728
		C	38.74 (3.26)	32.46 (3.38)	1.3397	8.0	0.2171
		C/N	40.51 (2.41)	38.32 (1.22)	0.8126	8.0	0.4406
JE	Oi	N	0.82 (0.04)	0.96 (0.32)	-0.4501	1.0	0.7299
		C	46.68 (1.25)	44.43 (1.58)	1.1167	5.0	0.3643
		C/N	57.78 (3.40)	52.65 (19.19)	0.2634	1.1	0.8348
	Oa+Oe	N	0.90 (0.03)	0.93 (0.07)	-0.3558	8.0	0.7312
		C	37.15 (2.52)	36.47 (2.85)	0.1799	8.0	0.8617
		C/N	41.70 (3.91)	39.86 (3.24)	0.3633	8.0	0.7258
DD	Oi	N	0.89 (0.06)	1.17 (0.16)	− 1.6586	8.0	0.1358
		C	47.03 (0.92)	43.84 (4.54)	0.6875	4.3	0.5272
		C/N	54.30 (4.40)	38.40 (3.30)	2.8718	8.0	0.0208
	Oa+Oe	N	1.00 (0.08)	1.22 (0.09)	-1.7130	8.0	0.1251
		C	35.07 (3.55)	37.22 (2.15)	-0.5161	8.0	0.6194
		C/N	34.80 (2.05)	30.80 (1.20)	1.6926	8.0	0.1294

NOTE: Data in parentheses are standard errors.

TABLE 5. Nitrogen loss proportions by site and type of pool ($kg\ N \cdot ha^{-1}$ loss per $Mg\ ha^{-1}$ mass consumed)

Site	Wood	Foliage	Forest floor	
			Oi	Oe+Oa
JW	2.7	14.0	9.0	16.0
JE	2.7	12.0	8.0	7.0
DD	2.6	12.0	8.0	—

uals, a 70% reduction in litter weight, and a 30% reduction in root-mat weight for an oak-pine community in the southern Appalachians of South Carolina. In a mid-Appalachian pine community, the upper forest floor (Oi + Oe combined) was totally consumed by low- and high-severity wildfires, but the low-severity fire left the Oa layer intact (Groeschl et al. 1990). In contrast with our study, N and C increased in the remaining Oa layer (Groeschl et al. 1990). Kodama and Van Lear (1980) found significant reductions of both mass and N in the Oi layer, but no significant changes in the Oa + Oe layer following prescribed burning of a loblolly pine plantation in the Piedmont of South Carolina. Other studies of harvest and site preparation burning in a variety of southern pine forests have documented N losses from harvest ranging from 52 to 345 $kg \cdot ha^{-1}$ and N losses from slash and forest floor as high as 112 $kg \cdot ha^{-1}$ (Neary et al. 1984; Tew et al. 1986). The wide range in mass and N losses is related to differences in fire intensity and severity and to the size of the pools before burning.

Even without the removal of large woody material, losses of N (376, 480, and 193 for JW, JE, and DD, respectively) were in the middle to upper range of values for southeastern pine forests. Taken across sites, N losses from burning represent about 20% of the total soil N pool to a 20-cm depth (Knoepp and Swank 1993). The implications of this N loss must be considered in the context of important N cycling processes such as rates of N deposition, biological fixation, immobilization, mineralization, and availability associated with successional forests. Simulation models of the N cycle provide a tool for evaluating the long-term consequences for alternative management practices on site productivity (Swank and Waide 1980) and, as our study progresses, will be used to assess implications of burning on productivity. Nitrogen losses in our study are comparable with those for whole-tree harvests (excluding foliage) on higher quality hardwood sites in the southern Appalachians (Mann et al. 1988). For example, in nearby mixed hardwood stands at the Coweeta Hydrologic Laboratory, N removal associated with whole-tree harvesting was estimated to be 280 $kg \cdot ha^{-1}$ (Swank 1984).

As in other studies (Schoch and Binkley 1986; Little and Ohman 1988; Feller 1988), N losses were proportional to mass consumption. These proportions were consistent across sites for wood (e.g., 2.7, 2.7, 2.6 kg $N \cdot ha^{-1}$ per $Mg \cdot ha^{-1}$ mass consumption, for JW, JE, and DD, respectively) (Table 5). Proportions were slightly greater for foliage and forest floor on JW, perhaps reflecting the importance of hardwood foliage on JW (Table 2), which has a greater nutrient content than pine or mountain laurel foliage. By comparison, Schoch and Binkley (1986) summarized data from prescribed burns with a wide range in severity in loblolly pine stands and found N loss proportions of 5 to 10 kg N/Mg mass consumed. These values are comparable with our values for N loss proportions in the Oi layer (i.e., 8 to 9 kg N/Mg mass consumed).

Identification of key pools contributing to N and C losses

Across all sites, the largest pools of N and C were in the wood and forest floor. Hence, patterns of consumption of these fuels in a prescribed fire dictate the magnitude of losses. Foliar pools are also important, but prescribed fires similar to the ones we studied are likely to consume most foliage still attached to felled trees. One objective of the prescribed burning is to reduce the quantity of woody debris on the site to facilitate planting. Because of the large woody N pool, loss of total site N will increase substantially as more of this mass is consumed. However, the immediate importance of this N loss is low because this N becomes available very slowly as the woody material decomposes. However, this N loss may have long-term site productivity implications.

The forest floor is a more labile and immediate N source because its decomposition and mineralization provide a steady and relatively large amount of available N to the site. In this study, the Oi layer was nearly completely consumed on JW and JE and contributed 25 to 30% of the total N lost. The Oi layer was reduced by about 50% on DD, but the loss of N was still about 25% of the total N lost. The Oe + Oa layer was not significantly reduced by the fires. Thus, a major pool of potentially available N remained relatively intact. Chemical changes in the forest floor may alter decomposition rates, but we found no consistent changes in N concentration, C concentration, or C/N ratio of either the Oi or Oa + Oe layers. Other studies have found increases (Little and Ohmann 1988; Groeschl et al. 1990), decreases (Little and Ohmann 1988), and no change (Little and Ohmann 1988). This variation is primarily related to differences in fire severity. In some studies, changes in the microclimate (i.e., warmer and wetter) have increased decomposition and net N mineralization and, hence, resulted in increased N availability of the site (White 1986; Schoch and Binkley 1986). In a related study, slight increases in net N mineralization were observed on the JE site (Knoepp and Swank 1993). Maintaining an intact forest floor is, and should remain, a major objective of the burning prescription. Silviculturalists must balance the desire to reduce woody debris with the need to maintain forest floor mass.

Site differences

Fuel load, size distribution, flammability, and moisture content interact to determine a fire's fuel consumption and the amount of energy release (Martin et al. 1979). Absolute and proportional mass, N, and C losses were greatest on JE. Factors contributing to the magnitude of loss are the quantity, type, and distribution of fuels. On JE, the total prebum fuel load was 224.2 $Mg \cdot ha^{-1}$ and the dominant woody components comprised pine in the >10 cm class and mountain laurel in the 510 cm class (Table 2). Both the quantity and the dominance of highly flammable fuels contributed to greater mass, N, and C consumption. As a percent of preburn totals, mass losses on JW and DD were comparable, but considerably less N was lost on DD. On DD, losses of mass and N from the forest floor were lower. On the days of the bum, forest floor moisture contents were 59, 77, and 99% for the JW, JE, and DD sites, respectively (Ottmar and Vihnanek 1991). The high percent moisture of the forest floor on DD reduced the severity of the fire. Percent loss of woody mass may have been greater on DD than on JW because of the importance of pines and mountain laurel in the prebum fuels (Table 2). In addition, trees were considerably smaller on DD than on either JW or JE (Table 1). Smaller sized fuels are consumed more efficiently than large fuels (Martin et al. 1979).

Summary and conclusions

The objectives of felling and burning were to reduce logging slash to facilitate planting and to minimize hardwood competition with planted pine seedlings. The treatment clearly achieved the objective of slash reduction for planting. Pine seedling establishment and competition are reported in another paper (Elliott and Vose 1993). The major pools of mass, N, and C were contained in the woody material and the forest floor. Hence, losses from these pools dictate the magnitude of ecosystem losses. Maintaining an intact forest floor should be a high priority. This requires a balance between the desire to reduce logging slash and competition while minimizing forest floor consumption. Nitrogen loss was proportional to mass loss, and amounts ranged from 193 to 480 kg $N \cdot ha^{-1}$. Results from Knoepp and Swank (1993) indicated no significant changes in total soil N, so we can conclude that the aboveground and forest floor N losses were exported from the site. These losses are comparable with those from whole-tree harvest studies on higher quality sites in the southern Appalachians. Sites receiving the fell and bum treatment are typically infertile; for example, Knoepp and Swank (1993) reported extremely low levels of soil inorganic N availability on these sites (e.g., $<2\ mg \cdot kg^{-1}$). Nitrogen losses of this magnitude on low-quality sites may indicate a need for caution with regard to impacts on long-term productivity. As our ecosystem study progresses and more results become available, we will have a better assessment of the long-term productivity implications.

Variation in the patterns of mass, N, and C consumption reflected the complex relationships among fuel type, amount, size distribution, and moisture content. For example, the "best bum" occurred on DD, where a substantial quantity of aboveground material was removed with minimal forest floor reduction. Conditions promoting this type of bum included a large proportion of smaller woody fuels and a very moist forest floor (percent moisture = 99%). Understanding conditions contributing to this variability in patterns of mass, N, and C consumption may assist in prescribing future bums.

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