FUELS CONSUMPTION AND NITROGEN LOSS FOLLOWING PRESCRIBED FIRE: A COMPARISON OF PRESCRIPTION TYPES IN THE SOUTHERN APPALACHIANS

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Abstract—Prescribed burning is frequently used as a tool for restoration of plant communities, wildlife habitat improvement, and site preparation. We compared and contrasted the effects of four burning prescriptions on forest floor and fine fuels consumption, and nitrogen loss. The burning treatments included dry (DU) and mesic (MU) understory burns, stand replacement (SR) burning, and fell and burn (FB) site preparation. On all sites, forest floor was sampled before and immediately after burning. It was separated into woody fuels (< 7.5 cm in diameter), the Oi layer (litter), and the Oa + Oe layer (fermentation plus humus), and dry weight and nitrogen content of each component was determined. Tiles with heat-sensitive chalk and paint were used to estimate flame intensity at 30 cm above the forest floor. Mean peak flame temperatures ranged from 700 ºC for the FB treatment to 169 ºC for the MU burn. Except in the FB treatment, which had a substantial amount of woody mass on the forest floor as a result of felling overstory trees and shrubs, the majority of pre-burn mass and nitrogen was contained in the humus layer. Following burning, mass loss ranged from 88 Mg ha^{-1} (90 percent wood, 10 percent litter, < 5 percent humus) on the FB treatment to 5 Mg ha^{-1} (5 percent wood, 55 percent litter, 40 percent humus) on the MU burns. Nitrogen losses followed similar patterns – 292 kg ha^{-1} (70 percent from wood, 28 percent litter, <5 percent humus) on the FB to 30 kg ha^{-1} (65 percent from wood, 35 percent litter, <5 percent humus) on the SR site. High-intensity ground fires may result in greater losses of site nutrients, and this may have negative short- and long-term consequences.

INTRODUCTION

In many ecosystems, fire is used as a management tool to enhance and protect overall stand health and productivity by reducing fuel loadings, thereby reducing the threat of catastrophic fire (Sanders and Van Lear 1987, Van Lear and Waldrop 1989). Prescribed fire can also be used to reduce competition that affects commercially desirable tree species and improve habitat for terrestrial wildlife (Cooper 1971). The use of fire to accomplish these goals is considered an attractive alternative to mechanical techniques of stand improvement, primarily because of reduced costs (Cooper 1971, Abercrombie and Sims 1986). The continued (and expanded) use of prescribed fire in the southern Appalachians and elsewhere has raised interest in its effects on ecosystem integrity. Scientists are especially interested in determining how fire influences losses of key plant nutrients such as nitrogen (N). Although total N pools are frequently in greater supply than is needed for plant growth, N is commonly a limiting nutrient to forest productivity (Keeney 1980, Vitousek and others 1982) because most is in unavailable organic forms (Vose 2000). Total ecosystem nitrogen may decrease in forested systems following fire (Neary and others 1984, Rapp 1990) due to volatilization of nitrogen stored in coarse and fine fuels, or to increased leaching of released NO_3 from the system, or to both of these causes (Knoepp and Swank 1993). In contrast, increases in total N following burning can result from a combination of increased abundance of symbiotic and non-symbiotic N-fixers. Similarly, N availability often increases due to increased N mineralization and decreased plant uptake (DeBano 1991).

Nitrogen losses during and following prescribed fire in southern forests range from 20 kg ha^{-1} for low-intensity understory burns (Kodama and Van Lear 1980) to >400 kg ha^{-1} for high-intensity site preparation burns in heavy fuels (Vose and Swank 1993, Clinton and others 1996). The significance of

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these losses depends on inherent site productivity and the magnitude and duration of changes in N pools and cycling rates (Wells and Morris 1982, Vitousek and Matson 1985). In pine-hardwood ecosystems in the southern Appalachians, Knoepp and Swank (1993) found that net soil N mineralization increased immediately following cutting and burning and remained higher than that in control plots for about 2 years. Similarly, Dudley and Lajtha (1993) found N availability increased following prescribed fire in a sandplain grassland and remained higher than pretreatment levels for 3 years. Increased N mineralization rates can offset total N losses from fire; however, the degree to which N losses are ameliorated depends on the magnitude and source (i.e., forest floor vs. wood) of N losses and subsequent N recovery. In southern Appalachian hardwood ecosystems, forest floor losses are particularly important because release of N from the forest floor provides approximately 50 percent of the total available N (Monk and Day 1988). Our objective in this paper is to describe and compare variation in woody and fine fuels mass consumption and N losses across a range of prescribed fire types.

METHODS

Study Site Descriptions

Sites represented in this comparison span 15 years of fire research under a variety of conditions and objectives. To simplify the comparison we assigned each treatment to one of four categories: (1) fell and burn (FB) site preparation, (2) stand replacement (SR) burning, (3) understory burning on dry sites (DU), and (4) understory burning on moist sites (MU). The fell and burn site preparation treatment was developed by Abercrombie and Sims (1986) for pine-hardwood ecosystems in the mountainous region of South Carolina. As the treatment was originally conceived, merchantable products were to be removed and all other vegetation felled in the spring after leaf-out; then a mid-summer burn would be used to consume slash and sprouting vegetation. On our FB sites no products were removed and all vegetation was cut by chainsaw during the summer of 1990. Cut vegetation cured for 44 to 90 days before burning, and sites were burned in early fall with a hand-set fire that produced a high-intensity but low-severity fire (Ottmar and Vihnanek 1991). Average fuel moisture (for all size classes) at the time of burning varied from 28 percent to 37 percent (Swift and others 1993, Vose and Swank 1993). The FB study sites were located on the Wayah Ranger District of the Nantahala National Forest in western North Carolina (Clinton and others 1993, Elliott and Vose 1993, Knoepp and Swank 1993, Swift and others 1993, Vose and Swank 1993, Clinton and others 1996, Elliott and others 2002). Pretreatment stand age was approximately 80 years (Swift and others 1993), and average basal area and density (stems >10 cm in diameter at breast height (d.b.h.)) were 14.8 $m^2 ha^{-1}$ and 461 stems ha^{-1}, respectively (Vose and Swank 1993). Sites were selected as replicates and had similar pre-treatment vegetation structure, topographic position, aspect, and soil type (Swift and others 1993).

The SR burn was located on the Wayah Ranger District of the Nantahala National Forest in western North Carolina and was part of the Wine Spring Creek Ecosystem Management Project (Swank and others 1994, Vose and others 1999). The site consisted of an overstory in various stages of decline that ranged from dead pines and heavy fuels on the upper slope positions to degraded (dead and dying) mixed pine-hardwood overstory on the mid-slopes. The area was approximately 150 ha, had a southeast aspect, ranged in elevation from 1000 to 1300 m (3,300 to 4,300 feet), and had slopes ranging from 35 to 60 percent. Mean annual temperature is 10.4 ºC (50 oF) and annual precipitation is approximately 1900 mm (75 inches). The stand replacement prescription fire was set in late April by helicopter using a combination of heli-torch and ping-pong balls (potassium permanganate). See table 1 for additional site descriptions.

The DU study sites were located in north Georgia on the Cohutta and Tallulah Ranger Districts of the Chattahoochee National Forest and in southeast Tennessee on the Ocoee Ranger District of the Cherokee National Forest (see Hubbard and others 2004). These sites were part of the USDA Forest Service Large-Scale Watershed Restoration Project. All sites had about 50 percent of the stand basal area in yellow pine, consisting of one or more of pitch pine (*Pinus rigida*), Table Mountain pine (*P. pungens*), Virginia pine (*P. virginiana*), loblolly pine (*P. taeda*), and shortleaf pine (*P. echinata*). Sites were burned in the late winter or early spring season with a mix of hand-set and helicopter-set ignitions.

Table 1—Site descriptions for the four burn types. Helicopter-set burns were ignited by a combination of heli-torch and ping-pong balls (potassium permanganate). Hand-set fires were set with handheld drip torches. Temperature is mean peak flame temperature at 30 cm above the forest floor. “Preburn woody fuels” is material on the forest floor

Burn type	Timing	Ignition type	Elevation	Preburn woody fuels	Mean temperature	Temperature range
			m	*kg ha^{-1}*	- - - - - - - - - - *°C*	- - - - - - - - - -
FB (1)	Late summer	Hand	750 – 1000 (2,460 – 3,280)	183 717 (163,912)	712 (1,314)	276 – 800+ (529 – 1,470+)
SR (1)	Early spring	Helo	1000 – 1300 (3,280 – 4,260)	15 773 (14,073)	560 (1,040)	80 – 800+ (176 – 1,470+)
DU (2)	Late winter	Helo/hand	350 – 900 (1,150 – 3,000)	15 000 (13,383)	238 (478)	52 – 700 (126 – 1,292)
MU (3)	Late winter	Helo/hand	350 – 1200 (1,150 – 4,000)	3 400[a] (3,033)	169 (336)	80 – 276 (176 – 529)

FB = fell and burn; SR = stand replacement; DU = dry understory; MU = mesic understory.
Values in parentheses under “Burn type” represent the number of studies included for each type.
Values in parentheses under “Elevation,” “Preburn Woody Fuels,” “Mean Temp,” and “Temperature Range” are standard English equivalents in feet, lbs ac^{-1}, and degrees Fahrenheit, respectively.
[a] Value is for woody fuels < 7.5 cm (3 inches) diameter.

The MU study sites were (1) a high-elevation site in western North Carolina on the Wayah Ranger District of the Nantahala National Forest and (2) an approximately 300-ha south-facing watershed on the Tallulah Ranger District of the Chattahoochee National Forest in northeast Georgia. The sites were mixed hardwood with a small yellow pine component and scattered to continuous understory of *Rhododendron maximum* and *Kalmia latifolia*. Aspects ranged from south-facing at the low-elevation site to east-facing at the high-elevation site. A combination of hand-set and helicopter-set ignition was employed (table 1).

Forest Floor

On each site, 10 by 20 m plots were established to characterize vegetation and other processes associated with studies examining a range of ecosystem responses that are not reported here. Forest floor mass was measured for each site before and immediately after burning. Forest floor samples were collected from four locations in each 10 by 20 m plot by cutting and removing all material in a randomly located square (0.1 m^2) sampling frame. Forest floor was separated into small woody material (< 7.5 cm diameter), Oi (litter), and Oe+Oa (fermentation and humus) layers. Pre- and post-burn coarse wood (>7.5 cm) mass was quantified on each 10 by 20 m plot using pre and post diameters and estimates of specific weight for the range of observed decay classes. Coarse wood amount was not estimated on the MU sites. Forest floor samples were dried at 70 ºC to a constant weight. Forest floor mass estimates were not ash free corrected; however, care was taken during sampling to minimize mineral soil contamination. Each sample was completely ground through a 1 mm mesh, homogenized, and subsampled for nutrient determination. Percent N was determined using a Perkin-Elmer 2400 CHN elemental analyzer. Estimates of N pools for each forest floor component were made by multiplying percent N times mass.

Fire Characterization

We used heat sensitive chalk and paint (Omega Engineering, Inc.) coated 10 cm by 20 cm tiles to characterize the temperature of the burns. On the day before the burn, we suspended the temperature tiles

30 cm above the forest floor co-located with forest floor subplots (four tiles per plot). Each tile could detect 30 temperature thresholds ranging from 52 ºC to 900 ºC.

Data Summary and Analysis

Comparisons were made between prescription types for pre- and post-burn mass and N pools. Statistical differences in pre- and post-burn N concentrations in wood, litter, and humus were evaluated for each site at the 0.05 level with analysis of variance (PROC ANOVA, SAS Inst. 1994). Since most the data used in this paper were derived from retrospective watershed scale studies, we have limited our analyses to descriptive statistics and qualitative comparisons of fuels consumption and N losses. While this approach limits the ability to make inferences about responses in other watersheds and burning treatments, the long-term and integrative nature of watershed scale studies has long been recognized as a powerful approach for understanding ecosystem responses to disturbance (Swank and Vose 1997).

RESULTS AND DISCUSSION

Pre-Burn Conditions

Total pre-burn mass was substantially greater (3- to 8-fold) on the FB compared with the SR, MU, and DU burn sites, due primarily to the felled woody material (fig. 1a), and to a lesser extent the additional leaf litter from felled material. Mass of woody fuels on SR sites was generally similar to that on DU sites, but mass of woody fuels on the MU sites was considerably less. Forest floor mass, separated into Oi (litter) and Oa + Oe (fermentation and humus), varied among study sites. Litter was greatest on the FB sites and least on the MU sites, whereas humus amounts were greater on the DU sites and least on the SR site (fig. 1a). The lower amount of litter humus on the MU sites is likely due in part to faster decomposition rates on those more productive sites. In contrast, slower decomposition on the DU sites most likely resulted in greater litter and humus accumulation. There were scattered live fuels on all sites in the form of the evergreen shrubs mountain laurel (*Kalmia latifolia*), primarily on the driest sites, and rosebay rhododendron (*Rhododendron maximum*) on the moist sites, as well as various deciduous ericaceous species. Both evergreen shrub species are sclerophyllous, producing foliage high in waxy compounds that increase flammability (Hough 1969). Under the right conditions, these species can act as fuel ladders in these ecosystems (Waldrop and Brose 1999).

Pre-burn N concentrations in woody and fine fuels are shown in table 2. Typically, woody material has a low N concentration relative to litter and humus but can represent a substantial pool of site N on sites with heavy woody fuels (Harmon and others 1986, Vogt and others 1995). The highest N concentrations, and typically the largest N pools, are typically in the humus layer. In southern Appalachian ecosystems, as much as 50 percent of the total plant available N is provided by the forest floor, much of it by the humus layer (Monk and Day 1988). On our study sites, the humus layer accounted for 40, 74, 76, and 86 percent of total pre-burn N on the FB, SR, MU, and DU sites, respectively (fig. 1b). Although pre-burn humus N concentrations were greater on the MU sites than on the DU sites, there was substantially more humus mass on the DU sites contributing to the greater amount of total N in that layer.

Fire Characteristics

Fire intensity varied across burn types, with the greatest mean peak flame temperatures occurring on the FB treatment (table 1). The range in flame temperatures varied considerably among burn types (table 1). Heavy, dried fuels on the FB site contributed to a greater mean peak flame temperature. Variation in mean peak flame temperature and maximum temperature may be explained by timing and ignition source. For example, in the case of heli-torch or ping-pong balls, fire intensity increases with decreasing placement density. That is, the wider apart the burn initiation points the more room the fire has to run before encountering burned areas, which can result in more intense fires.

Fuels Consumption

Consumption of woody and fine fuels varied among burn treatments and was greatest on the FB treatment. Total fuels consumption ranked FB>DU>SR>MU with the majority of consumption coming from the

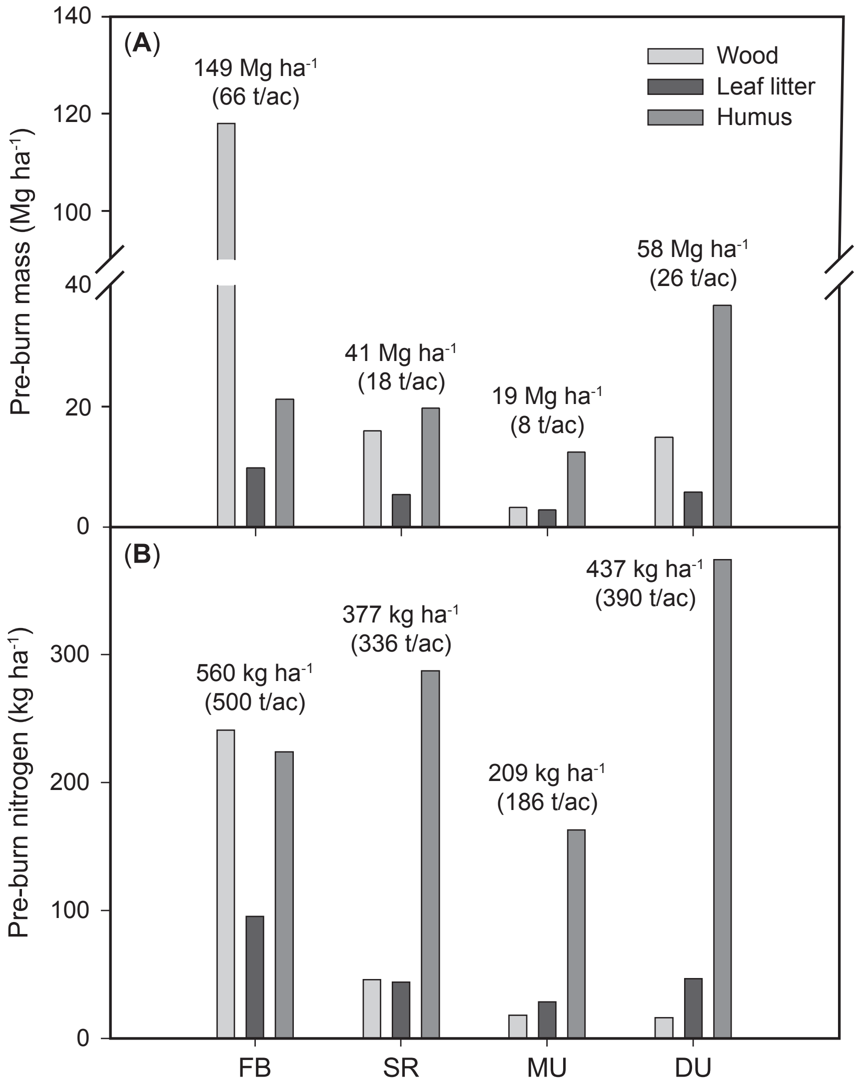

Figure 1—Pre-burn mass (A) and total nitrogen (B) by prescription and material type. Values within each panel represent site totals. Values in parentheses are standard English equivalents. Wood for mesic understory is fine woody fuels < 7.5 cm (3 inches) in diameter only.

Table 2—Nitrogen concentrations in percent for wood, litter, and humus before and after burning by site[a,b]

Site	Wood	Litter	Humus
	- - - - - - - -	*percent*	- - - - - - - -
FB			
Pre N	0.25 n.a.	0.89 n.a.	0.95 n.a.
Post N	0.36 n.a.	1.13 n.a.	1.00 n.a.
SR			
Pre N	0.54^{a} (0.03)	0.97^{a} (0.03)	1.48^{a} (0.06)
Post N	0.50^{a} (0.06)	1.10^{a} (0.10)	1.56^{a} (0.04)
MU			
Pre N	0.45^{a} (0.03)	0.77^{a} (0.02)	1.14^{a} (0.02)
Post N	0.51^{a} (0.02)	1.07^{b} (0.03)	1.22^{a} (0.01)
DU			
Pre N	0.40^{a} (0.01)	0.76^{a} (0.01)	1.10^{a} (0.02)
Post N	0.38^{a} (0.02)	0.93^{b} (0.02)	1.00^{a} (0.02)

FB = fell and burn; SR = stand replacement; MU = moist understory burn; DU = dry understory burn.

[a] Values in parentheses are standard errors.

[b] Means within material type and site with the same superscript are not significantly different at the 0.05 level

wood component on the FB and SR sites and from the litter component on the MU and DU sites. Wood (almost 80 Mg ha^{-1}) made up nearly 90 percent of the total mass lost on the FB sites, whereas <5 Mg ha^{-1} of wood was consumed on each of the other sites (fig. 2a). Of the total mass of 6 Mg ha^{-1} consumed on the SR site, almost 65 percent was woody material, whereas on the DU and MU sites approximately 20 percent and 10 percent, respectively, was woody material, although total mass loss was similar on those three sites (fig. 2b). Differences in proportional consumption (i.e., wood vs. litter vs. humus) between the SR, DU, and MU sites was primarily due to the amount of humus consumed. Very similar amounts of humus were consumed on the FB, DU, and MU sites, while the SR site lost a smaller amount of humus. All burns were characterized as having high intensity and low severity, which is essential for minimizing humus consumption and the resulting loss of site nutrients. Although total pre-burn mass of wood was very similar to total pre-burn mass of humus on the SR site, the quick burn resulted in minimal humus consumption. Shorter fire residence times reduce the likelihood that significant losses of site nutrients will occur through humus consumption.

Nitrogen Losses

The greatest loss N during burning occurred on the FB site. Before burning, the amounts of N in woody material and humus on that site were roughly equal. However, most of the mass loss came from the woody component, and, although N concentrations were low, total N losses were great (fig. 3a). Similarly, most of the N loss on the SR site came from the woody component, although the total amount lost was an order of magnitude less. More importantly, the majority of the N lost from the MU and DU sites (50 and 65 percent, respectively) came from the humus layer. Even though more mass was lost from the litter layer on those sites, higher N concentrations in the humus layer resulted in a greater proportion of total site N lost from that layer (figs. 3a, 3b). Total amounts were low relative to the extreme condition found on the FB site but the loss of N from the humus layer can have immediate and long-term consequences for site productivity.

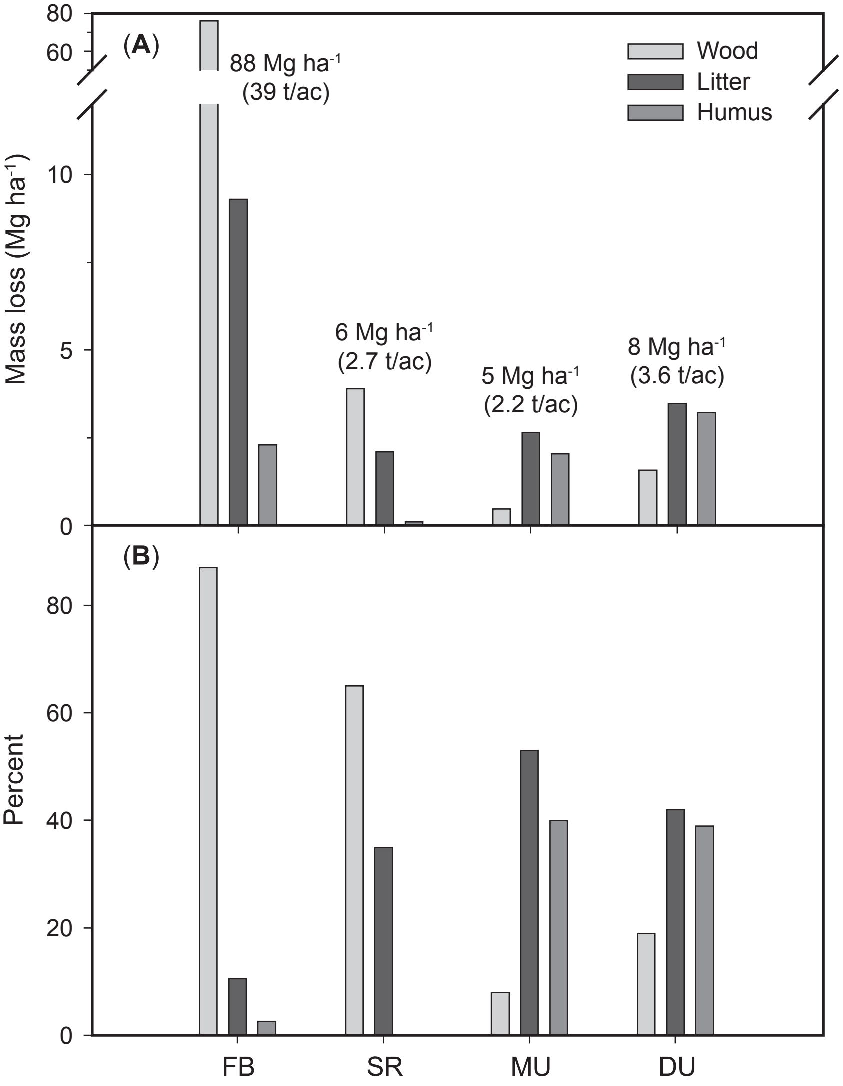

Figure 2—Mass consumption (A, in Mg ha^{-1}) following burning and percent of total loss (B) by site and material type. Values in (A) represent total loss for each site. Values in parentheses are standard English equivalents.

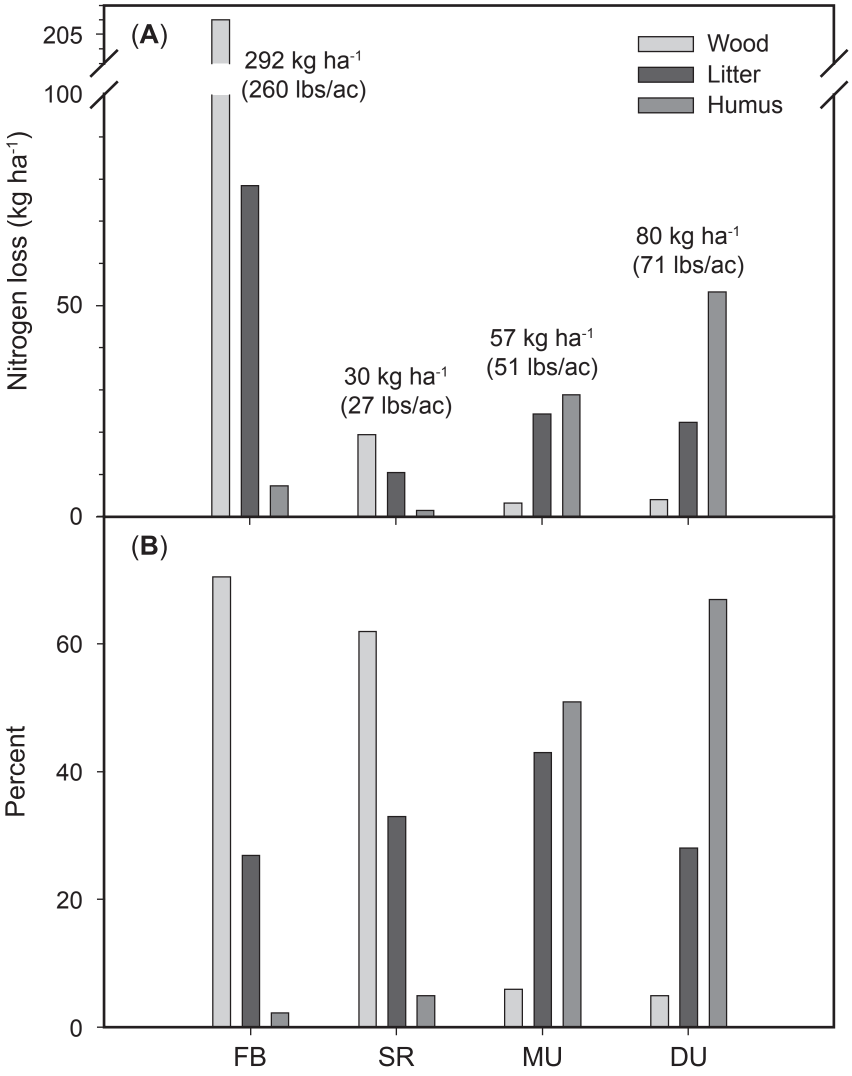

Figure 3—Nitrogen losses (kg ha^{-1}) (A) and percent of total loss (B) by prescription and material type. Values in panel (A) represent total loss for each site. Values in parentheses are standard English equivalents.

Implications for Management

Fire managers cannot control fire weather but they can control ignition timing and type, and consequently fire intensity. Under all site conditions, the longer a prescribed fire persists in one place the more intense the fire and the more likely there will be significant consumption of the humus layer. Minimizing consumption of the humus layer has important implications for long-term site productivity, as this layer is typically the largest reservoir of available site nutrients in these ecosystems. This is particularly important during the post-burn recovery period when young woody and herbaceous seedlings are becoming re-established (Clinton and Vose 2000). Although the short-term loss of site nutrients, particularly nitrogen, is inevitable during burning, prescribed burning can enhance overall site quality and productivity over the long-term by stimulating nitrogen cycling processes. The significance of N losses and time required for recovery and enhancement of N cycling processes varies considerably by ecosystem type and the severity and intensity of the prescribed fire. For example, when total site N pools are small, as was the case on the MU sites, any loss of N — and especially any loss from the humus layer — can represent a substantial fraction of the pre-burn total and increase the risk of negative impacts. Burning under such conditions requires careful planning in order to not compromise near-term site recovery or long-term site productivity.

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