Prescribed Fire and Herbicide Effects on Soil Processes During Barrens Restoration

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Abstract

Prescribed fire has become a common tool of natural area managers for removal of non-indigenous invasive species and maintenance of barrens plant communities. Certain non-native species, such as tall fescue (*Festuca arundinacea*), tolerate fire and may require additional removal treatments. We studied changes in soil N and C dynamics after prescribed fire and herbicide application in remnant barrens in west central Kentucky. The effects of a single spring burn post-emergence herbicide, combined fire and herbicide treatments, and an unburned no-herbicide control were compared on five replicate blocks. In fire-plus-herbicide plots, fescue averaged 8% at the end of the growing season compared with 46% fescue cover in control plots. The extent of bare soil increased from near 0 in control to 11% in burned plots and 25% in fire-plus-herbicide plots. Over the course of the growing season, fire had little effect on soil N pools or processes. Fire caused a decline in soil CO_2 flux in parallel to decreased soil moisture. When applied alone, herbicide increased plant-available soil N slightly but had no effect on soil respiration, moisture, or temperature. Fire-plus-herbicide significantly increased plant-available soil N and net N transformation rates; soil respiration declined by 33%. Removal of non-native plants modified the chemical, physical, and biological soil conditions that control availability of plant nutrients and influence plant species performance and community composition.

Key words: **exotic species control, *Festuca arundinacea*, invasive plants, Kentucky, nutrient cycling, net nitrogen mineralization, prairie, soil respiration, tall fescue.**

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Introduction

When European settlers reached the Big Barrens region of west central Kentucky during the late 1700s, they encountered a grass-dominated karst plain with few scattered oaks and hickories (Gorin 1876; Austin 1904). Repeated surface fires on shallow, droughty, or nutrient-poor soils historically maintained the prairie-like openings amid oak–hickory forest (Anderson et al. 1999). Fire suppression, conversion to agricultural land use, and invasion by non-native species caused the rapid disappearance of Kentucky's native barrens communities after settlement. Presently, there are no intact remnants of pre-settlement barrens in the region (Chester et al. 1997; Baskin et al. 1999). Scattered open-grown oaks, small grassy openings in the forest canopy, and patches of isolated herbaceous vegetation are the only traces of former barrens communities.

Currently, state and private agencies are working to improve and expand rare plant habitat in barrens communities at more than a dozen natural areas in west central Kentucky. Barrens habitats along the western Kentucky–Tennessee border contain 15 state- or federally-listed plant species (Chester et al. 1997). In these areas, managers attempt to reverse woodland encroachment and to eradicate non-native plants by linking natural disturbance processes with barrens community and ecosystem dynamics.

Prescribed spring burning is the main tool used to restore barrens grasslands. Fire is used primarily to manipulate plant community composition in favor of native forbs and warm-season grasses by eliminating woody invaders and non-native vegetation (Packard & Mutel 1997). However, although fire is effective at checking invasion by woody colonizers, it is often ineffective for removal of non-native grasses. For example, Washburn et al. (1999) found that a single spring burn reduced tall fescue (*Festuca arundinacea*) cover by a mere 6% (from 93 to 87%) at 10 study sites in Kentucky. Pretreatment cover of native grass species can contribute to the efficacy of fire as a control of non-native grass species. For example, prescribed fire has been shown to reduce the density of non-native smooth brome (*Bromus inermis* Leyss.) only when native warm-season grass cover is sufficient (>20%) to quickly outcompete the non-native grass (Willson & Stubbendieck 2000).

Where non-native species dominate plant communities and prescribed fire has been shown to be ineffective, herbicide application may offer a rapid vegetation management option (Willson & Stubbendieck 1996; Packard & Mutel 1997). In a site where prescribed fire alone failed to control tall fescue, application of the cool-season-grass-specific herbicide (Plateau, BASF-American Cyanamid, Raleigh, NC, U.S.A.) in conjunction with spring burning reduced its cover from more than 80% to less than 2% (Washburn et al. 1999; Washburn & Barnes 2000). In combination, fire and herbicide promote native warm-season grass establishment either with seeding or from residual seed reserves.

Linkages between fire and ecosystem processes, such as plant production and nutrient cycling, have been studied extensively in native grasslands (Knapp et al. 1998). In the tallgrass prairie surface fires increase the productivity of native warm-season grasses by removing accumulated surface litter, thereby increasing soil temperature and surface light intensity (Hulbert 1988). Fire increases belowground production (Seastedt 1988; Rice et al. 1998) and soil CO_2 flux (Knapp et al. 1998) and reduces soil N supply (Ojima et al. 1994; Turner et al. 1997) in burned compared with unburned grassland. Little is known, however, about ecosystem-level effects when prescribed fire is used as a tool for vegetation management after abandonment of agricultural lands. The effect of herbicides on soil processes and ecosystem dynamics is also largely unknown.

This study describes the influence of initial restoration activities in a Kentucky barrens ecosystem. The overall objective of this work was to assess the effect of prescribed fire and herbicide vegetation manipulations on microbially mediated soil N and C mineralization and on soil moisture and temperature. We hypothesized that as in tallgrass prairie, prescribed burning in western Kentucky barrens would reduce soil N supply and increase soil CO_2 flux within the first growing season and that herbicide combined with burning would increase these effects.

Methods

Site Description, History, and Management

The study was conducted at the Raymond Athey Barrens in Logan County, Kentucky (36°50′N; 86°48′W). The Kentucky State Nature Preserves Commission (KSNPC) has managed the 60-ha preserve since 1990. Mean annual rainfall and mean daily temperature at Bowling Green, Kentucky, 30 km east of the site, are 1,294 mm and 13.8°C, respectively. The site is located on the Kentucky Karst Plain (Baskin et al. 1999). Athey Barrens is situated on a broad ridge with areas of exposed Mississippian limestone interspersed within moderately deep (60–150 cm) typic Hapludalf soils of the Fredonia and Talbot series (Soil Conservation Service 1975). Surface soil pH is 6.6 (in water) with silt loam or silty clay loam texture.

The pre-settlement vegetation in the region was a mosaic of oak–hickory forest and grass-dominated barrens (Braun 1950; Baskin et al. 1999). Currently, little bluestem (*Schizachyrium scoparium*), big bluestem (*Andropogon gerardii*), and indiangrass (*Sorghastrum nutans*) are the principal grasses in barrens remnants (Cain & Castro 1959; DeSelm & Chester 1993; summarized in Baskin et al. 1999). Dominant canopy trees are post oak (*Quercus stellata*), blackjack oak (*Quercus marilandica*), and mockernut hickory (*Carya tomentosa*) with abundant eastern red cedar (*Juniperus virginiana*) and eastern redbud (*Cercis canadensis*). At the Athey Barrens 21 graminoid and 73 forb species have been identified, including the Kentucky state-listed prairie gentian (*Gentiana puberulenta*) and Carolina larkspur (*Delphinium carolinianum*) (KSNPC 1996).

Before formation of the preserve, the site was managed as pasture for over 50 years. The abandoned pastureland supports dense tall fescue stands mixed with broom sedge (*Andropogon virginicus*), ragweed (*Ambrosia bidentata*), and other grasses and forbs common to agricultural areas. The KSNPC's management objectives for the abandoned pasture areas of Athey Barrens include converting the tall fescue-dominated pastures into native warm-season grasslands.

Experimental Treatments and Design

Two adjacent abandoned pastures were partitioned into five treatment blocks, roughly 100 × 50 m each. The five blocks were aligned adjacent to one another. Initially, each treatment block was split into prescribed burn and unburned control areas (designated at random); after burning they were further divided into herbicide and no-herbicide control plots.

Prescribed fires were conducted on 23 March 1999 between 1300 and 1600 hours. Air temperature, relative humidity, and wind speed averaged 13°C, 29%, and 8 to 16 km/hr, respectively, during burning. Replicate rectangular units were burned sequentially. A backfire was first ignited on the downwind edge of the block. The backfire burned slowly against the wind and along the lateral edges. After backfiring three sides of the unit, a headfire was ignited and burned with the wind. Each burn unit was about 0.25 ha in size. Fire temperature was estimated using heat-sensitive paints (Tempil, South Plainfield, NJ, U.S.A.) representing the range from 50 to 500°C. For both backfire and headfire areas, air temperature was measured within the surface fuel layer (10 cm) and at 40 cm above the soil surface. The depth of the soil-heating front was also measured with painted mica sheets inserted vertically to 10-cm depth in both backfire and headfire zones.

Post-emergence herbicide was applied 1 month after the prescribed fire (19 April) as the tall fescue began to resprout. Plateau (BASF-American Cyanamid, Raleigh, NC, U.S.A.; active ingredient Imazapic) was applied at a rate of 0.18 kg active ingredient/ha (see Washburn and Barnes 2000 for details on herbicide application).

Sampling and Analysis

One week before the prescribed burn, grass litter was sampled from 0.1-m^2 quadrats (n = 10 per burn unit). Samples were oven dried (60°C for 48 hr), weighed, ground, and analyzed for total C and N content by dry combustion (LECO CNS-2000, St. Joseph, MI, U.S.A.). Pre-burn mineral soil samples were collected from the upper 10 cm of soil with a hand corer. Percent cover of herbaceous species, litter, and bare ground was quantified during June and September using the point intercept method in 1-m^2 quadrats (100 points per quadrat). Three quadrats were located randomly within each treatment plot.

Ion exchange resin bags were installed at 5-cm depth the day after the prescribed fire. Resin bags were prepared by sealing 14 mL of cation resins (ID no. C-251; Sybron Chemicals Inc., Birmingham, NJ, U.S.A.) and 14 mL of anion resins (ID no. ASB-1P) into separate nylon stockings. Within each of the five treatment blocks, 10 resin bags were installed in both backfire and headfire zones and 20 in unburned controls. During installation, care was taken to avoid contaminating the resin bags with ash; non-incubated field blanks were used to correct for ash contamination. Thirty days after installation resin bags were removed and anion and cation resins were extracted with 1M KCl and analyzed for NO_3^- and NH_4^+ by colorimetric spectrophotometry (Bundy & Meisinger 1994).

Net mineral soil N transformations were measured at monthly intervals throughout the growing season (four incubations). Net mineralization and nitrification rates were measured on soils maintained at uniform temperature and two moisture levels (see details below) during laboratory incubations (Binkley & Hart 1989). Mineral soil cores from the upper 10 cm were sampled with a bulb corer, transported within a plastic cooler, refrigerated at 4°C, and processed within 48 hr. An initial subsample was extracted with 1M KCl and analyzed for NO_3^- and NH_4^+ as described above. A second subsample was oven dried at 105°C for 24 hr to calculate the field gravimetric moisture content. A pair of 15-g subsamples was incubated for 14 days at 26°C at (1) field moisture content (dry) and (2) field capacity (moist). Field capacity was approximated as the gravimetric water content of a subsample wetted to saturation and allowed to freely drain for 12 hr. Periodically during the incubation samples were reweighed and wetted with distilled water to maintain them at a constant mass and moisture content. Field-capacity incubations were wetted to about 50% gravimetric moisture content; field-moist incubations ranged from 15 to 25%. After 14 days the incubated subsamples were extracted with 1M KCl and analyzed as described above. Net mineralization was calculated as the change in NO_3^- plus NH_4^+ and net nitrification as the change in NO_3 between initial and incubated extracts. During one sample period a set of 14-day in situ incubations was carried out in conjunction with laboratory incubations. Field incubations were performed inside loosely capped portions of polyvinyl chloride tubing (4 cm diameter) buried to 10-cm depth. Extractions, analysis, and calculations proceeded as outlined above.

Soil CO_2 efflux was measured bi-monthly using an in situ infrared gas analyzer fitted with a soil chamber (PP Systems, Haverhill, MA, U.S.A.). The change in chamber CO_2 concentration during a 120-second period was used to calculate soil CO_2 efflux. The CO_2 measurement chamber was located directly on the mineral soil surface, avoiding grass clumps, rodent burrows, and soil cracks. In unburned plots surface detritus was cleared to expose mineral soil, and the flux measurement sites were allowed to equilibrate for 5 minutes before sampling. Loose soil was packed around the base of the chamber to seal against leaks. Five flux measurements were taken at systematically spaced locations within each treatment plot. A corresponding soil temperature measurement (5-cm depth) was taken during each flux measurement near the base of the CO_2 chamber. On each CO_2 measurement date, gravimetric soil moisture was quantified from a soil sample (0–10 cm) composited from five subsamples per plot. Additionally, soil (5-cm depth) and air temperature (1-m tall shaded box) were measured at hourly intervals (Onset Corp., Bourne, MA, U.S.A.) in one control and one fire-plus-herbicide plot.

Total mineral soil C and N, soil pH (Thomas 1996), and Melich-III extractable phosphorus and cations (Melich 1978) were analyzed on soil sampled before the spring burns, 1 day after the burns, and 4 months after the treatments were installed. Bulk density was calculated for the upper 10 cm on field-moist mineral soil. Fine root biomass in the top 10 cm was estimated by gently dissecting moist soil cores on a 500-μm sieve and then hand sorting roots. Soil nutrient concentrations and root biomass were reported on a dry soil mass basis. The mineral soil bulk density was used to convert concentration data to a volumetric basis (kg N/ha).

Statistical Analyses

The four treatments (control, fire, herbicide, fire-plus-herbicide) were compared using a mixed analysis of variance model with treatment as a fixed effect and plot and the treatment-by-plot interaction as random effects (SPSS Inc., Chicago, IL, U.S.A.). Significant differences between treatment means were identified using Tukey's LSD means separation test and a 0.05 significance level.

Results

Prescribed Fire Conditions

During the spring burns average maximum air temperature in the fuel layer (10-cm height) ranged from 250 to 300°C in backfire areas and from 300 to 400°C in headfires ($n = 20$). At 40 cm above the surface average maximum air temperatures were 250 to 300°C in headfires and 150 to 200°C in backfires. Soil conducted a 50 to 100°C heating front an average of 0.75 cm ($n = 40$) and a maximum of 1.2 cm deep.

Before the burn dense grass litter covered close to 100% of the site; the standing stock of dry grass fuel averaged 617 g/m^2 ($n = 10$ per plot) with no significant differences among plot replicates ($p = 0.585$). Litter contained 51 g N/m^2. Prescribed burning removed 95 to 100% of grass fuels but did not consume fine or coarse woody debris.

Vegetation Management

Prescribed fire and herbicide applied individually reduced tall fescue from 46% cover to 29% and 17%, respectively. In combination, fire-plus-herbicide reduced it to 8% (Fig. 1). Fire alone had no effect on warm-season grass cover, but herbicide and herbicide plus fire increased their cover more than twofold. Bare soil and litter cover (data not shown) mirrored one another. Bare soil increased from near 0 in unburned treatments to 11 and 25% for fire and fire plus herbicide, respectively. Litter decreased from 20% in unburned plots to 5% in burned plots.

Soil Conditions

Fire increased the amount of mineral N captured by resin bags during the first month after the burn. The movement of extractable NO_3^- and NH_4^+ were 4.2 and 1.5 times greater in burned compared with unburned plots, respectively (analysis of variance $p = 0.000$ and 0.006 for NO_3^- and NH_4^+, respectively). The proportion of resin NO_3^- increased from 23 to 45% of the total resin N after burning. Resin N levels were similar between backfire and headfire zones.

Separately, neither fire nor herbicide significantly affected inorganic soil N pools over the course of the study (Table 1). Fire-plus-herbicide, however, increased soil NH_4^+ to 2.1 times more than controls ($p < 0.000$). Overall, soil NH_4^+ represented greater than 90% of the total KCl-extractable soil N. One day after prescribed burning, soil NO_3^- and NH_4^+ pools were 48% and 13% lower, respectively, in burned plots compared with unburned controls (0.86 vs. 0.45 μg NO_3^-/g soil and 2.72 vs. 2.40 μg NH_4^+/g soil for burned and unburned soils, respectively). Within a month soil NO_3^- and NH_4^+ returned to control levels (0.21 vs. 0.15 μg NO_3^-/g soil and 2.95 vs. 3.23 μg NH_4^+/g soil for burned and unburned soils, respectively). Herbicide alone increased soil NH_4^+ 50% over control soil 1 to 2 months after application.

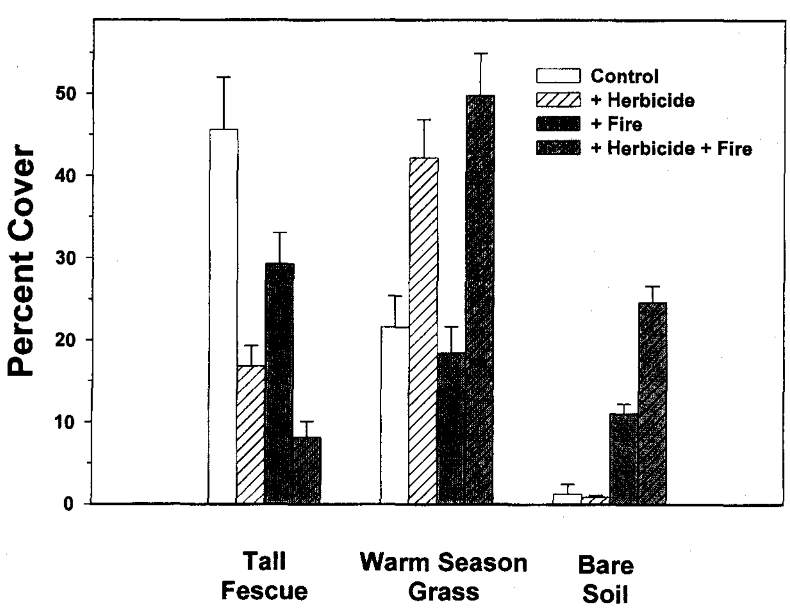

Figure 1. Plant cover during the 1999 growing season at Athey Barrens, Kentucky. Values are means (± SE) for five blocks of treatments with three 1-m^2 quadrats per treatment plot.

Table 1. Inorganic N pools and net N transformations in Athey Barrens soil after burning and herbicide application.

		Inorganic N				*Net N Transformations at Ambient Soil Moisture*				*Net N Transformations at Field Capacity*			
Management Treatment		*NH_4^+*		*NO_3^-*		*Mineralization*		*Nitrification*		*Mineralization*		*Nitrification*	
		kg/ha				*kg ha^{-1} 14 d^{-1}*				*kg ha^{-1} 14 d^{-1}*			
Control		2.04 b		0.03		0.55 b		0.90		5.20		2.78 b	
Herbicide		2.54 b		0.05		1.35 ab		0.97		5.78		2.89 b	
Fire		2.15 b		0.11		2.17 ab		0.64		4.01		3.54 b	
Fire + herbicide		4.38 a		0.05		4.06 a		1.36		7.40		6.54 a	
Source of Variation	df	F	p	F	p	F	p	F	p	F	p	F	p
Treatment	3	18.0	0.00	2.1	0.15	7.8	0.02	1.6	0.25	1.8	0.19	12.0	0.00
Block	4	2.2	0.13	2.7	0.08	0.9	0.51	1.9	0.18	0.5	0.75	3.2	0.05
Treatment × block	12	0.6	0.79	0.7	0.73	0.3	0.99	1.7	0.10	0.4	0.95	0.4	0.09

Data show means for three sample and incubation periods ($n = 15$). Within columns, different letters indicate significant treatment differences using Tukey's means comparison test and α of 0.05.

The production of inorganic soil N through mineralization and nitrification was greatest in fire-plus-herbicide plots for soils incubated both at original field moisture (dry) and when moistened to field capacity (Table 1). Fire and herbicide alone effected 2.4- and 4-fold increases in net soil mineralization compared with controls during field moisture incubations; this pattern disappeared when soils were wetted and incubated at field capacity. Fire-plus-herbicide soils nitrified 1.5 and 2.3 times faster than controls in dry and moist incubations. Control soils wetted to field capacity mineralized nearly 10-fold more than when incubated at their original field moisture content. Fire and fire-plus-herbicide treatments responded to wetting with 1.8-fold increases in net soil mineralization. Net soil nitrification rates increased more upon wetting in the fire and fire-plus-herbicide treatments.

Concurrent laboratory and field incubations of soil collected in mid-May indicated that net nitrification rates were more responsive to wetting than net mineralization (Table 2). During the incubation period in situ soil moisture content averaged 22% in unburned plots compared with 15% in burned plots and 49% in field capacity incubations. Overall, net soil nitrification increased from near 0 or slightly negative (indicating microbial immobilization of NO_3^-) to 2 to 6 kg NO_3^-/ha during the 2-week incubation. Net soil mineralization, in contrast, increased little after wetting. Mineralization did not differ among treatments.

Soil respiration fluctuated from 0.4 to 1.2 g CO_2 m^{-2} hr^{-1} over the course of the study with no clear seasonal trend. Herbicide had no effect on soil CO_2 release during the study period, but fire reduced the flux by 12% compared with control plots (Fig. 2a; $p = 0.000$). Soil respiration declined by 28% in the combined fire-plus-herbicide plots ($p = 0.000$). Unburned sites demonstrated a positive linear relation between soil temperature and soil CO_2 flux ($y = 0.02 \cdot [°C]) + 0.38$; $p = 0.000$; adj. $r^2 = 0.13$), whereas no significant relation existed in the burned plots ($p > 0.05$).

Similar to soil CO_2 release, herbicide did not alter soil moisture significantly, whereas fire ($p = 0.000$) and fire-plus-herbicide ($p = 0.000$) both dried soils appreciably (Fig. 2b). Soil temperature increased in the order control < herbicide < fire < herbicide + fire (Fig. 2b). On average, soil temperature was 6°C higher ($p = 0.000$) (Fig. 2b) and fluctuated more widely (Fig. 3) in the combined herbicide–fire plots compared with controls. Fire and herbicide reduced root biomass from 4.0 to 1.6 and 2.2 mg/cm^3. Fire-plus-herbicide generated no additional reduction in root biomass, suggesting that the decline in soil CO_2 efflux in the combined treatment results from lower soil microbial activity rather than merely reduced root respiration.

Extractable soil P, cations, and soil pH were similar between burned and unburned plots immediately after the fire (Table 3). Four months after the burn cations and soil pH remained unaffected by fire and herbicide treatments, whereas extractable P was 40% greater in burned treatments ($p = 0.007$).

Discussion

The Athey Barrens is currently in a state of rapid transition with regard to plant species, community structure, and disturbance regime. Restoration actions have shifted the disturbance regime from pasture management with fire suppression to short-term herbicide use and periodic spring burns. Monospecific tall fescue pastures are giving way to mixed-species warm-season grasslands. Patchy native grasses interspersed with bare soil are replacing the uniformly dense fescue sod and continuous litter. The lack of intact barrens in the region, however, prevents comparison of community composition and ecosystem processes in the restored Athey Barrens with an appropriate reference ecosystem.

Table 2. Net N transformations for soils incubated concurrently in situ and in the laboratory (initiated May 20).

		Net Mineralization		*Net Nitrification*		*Soil Moisture*	
		In Situ	*Laboratory*	*In Situ*	*Laboratory*	*In Situ*	*Laboratory*
		kg ha^{-1} 14 d^{-1}		*kg ha^{-1} 14 d^{-1}*		%	
Control		1.74	1.95	0.00 d	2.31 bc	20.5 bc	49.6 a
Herbicide		3.07	2.78	−0.02 d	2.08 b	23.6 b	52.3 a
Fire		2.16	2.22	0.80 cd	2.94 c	12.4 c	46.3 a
Fire + herbicide		1.90	3.03	0.04 d	6.08 bc	16.9 bc	48.2 a
	df	F	p	F	p	F	p
	7	0.3	0.97	10.9	0.00	43.0	0.00

Laboratory incubations were wetted and maintained at field capacity. ANOVA *F* ratio and *p* values for mineralization, nitrification, and soil moisture. Similar letters indicate significant treatment or incubation type (i.e., in situ vs. laboratory) differences based on Tukey's means separation test ($\alpha = 0.05$).

Consistent with tallgrass prairie (Hulbert 1988; Knapp et al. 1998) and forest (Kaye & Hart 1998) ecosystems, prescribed fire at Athey Barrens increased soil temperature dramatically. At Konza prairie soil temperature increased up to 6°C compared with the 4.5 and 6°C increases in fire and fire-plus-herbicide plots at the Kentucky Athey Barrens site. Soil moisture declined after burning tallgrass prairie (Garcia & Rice 1994; Turner et al. 1997), ponderosa pine-bunchgrass (Kaye & Hart 1998), and Kentucky barrens ecosystems.

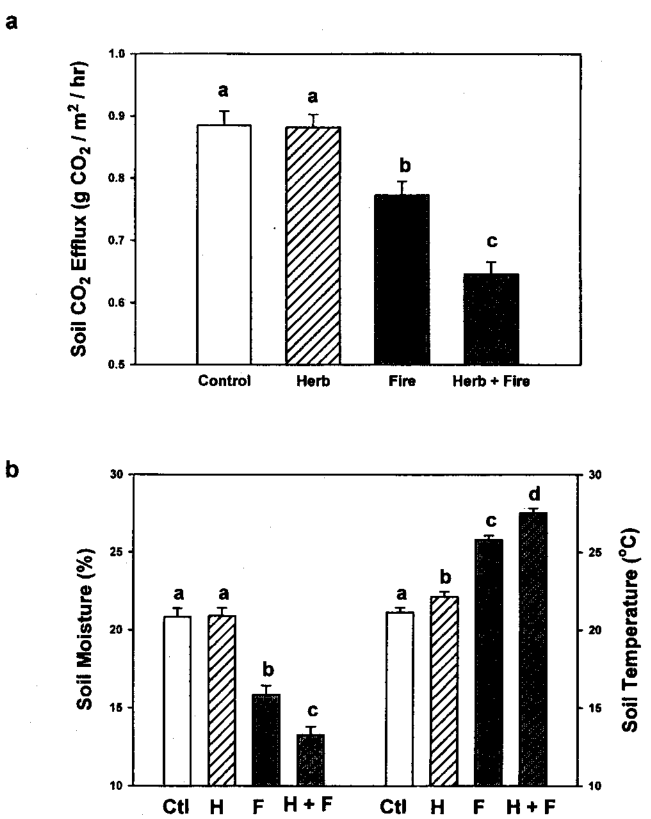

Figure 2. Soil CO_2 (a) and gravimetric soil moisture and soil temperature (b) during the 5-month study period. Bars are means (± SE) for seven sample dates for fire and no fire controls ($n = 150$) and six sample dates for herbicide and fire-plus-herbicide plots ($n = 175$). For each response variable similar letters indicate that treatment means are equal based on Tukey's means separation test ($\alpha = 0.05$ critical level).

The effect of prescribed burning on soil N supply varies with the ecosystem type. Annually burned tallgrass prairie had lower extractable soil N and lower net mineralization rates than unburned controls (Ojima et al. 1994; Turner et al. 1997). Tallgrass prairie burned for the first time after prolonged fire suppression also demonstrated reduced soil N supply, though to a lesser extent than sites burned yearly. Conversely, in forest ecosystems combustion of forest floor material increases soil NH_4^+ immediately after prescribed fire; this pool of inorganic N may remain above original levels for months (Covington & Sackett 1992) or longer (Giardina & Rhoades 2001). With time soil NH_4^+ is depleted by plant uptake or converted to soil NO_3^- via nitrification.

Typically, soil C efflux increases after prescribed fire (Knapp et al. 1998; Kaye & Hart 1998) in contrast to the reduction in soil respiration measured on burned plots at Athey Barrens. Under normal soil moisture conditions increased soil temperature after burning drives higher soil microbial activity and respiration rates. Under dry soil conditions, however, moisture limits microbial biomass (Garcia & Rice 1994) and reduces soil respiration (Kaye & Hart 1998).

Low summer rainfall during the 1999 growing season compounded typical post-fire soil drying and altered soil C and N dynamics at the Athey Barrens. Rainfall in western Kentucky for May through August 1999 was 56% of the 20-year average (NCDC 2000). The dry conditions constrained plant growth and nutrient uptake, resulting in elevated soil NH_4^+ pools and measured most dramatically in the fire-plus-herbicide plots. Low soil respiration in the burned plots suggests that microbial activity was inhibited by soil dryness more than it was favored by increased soil temperature.

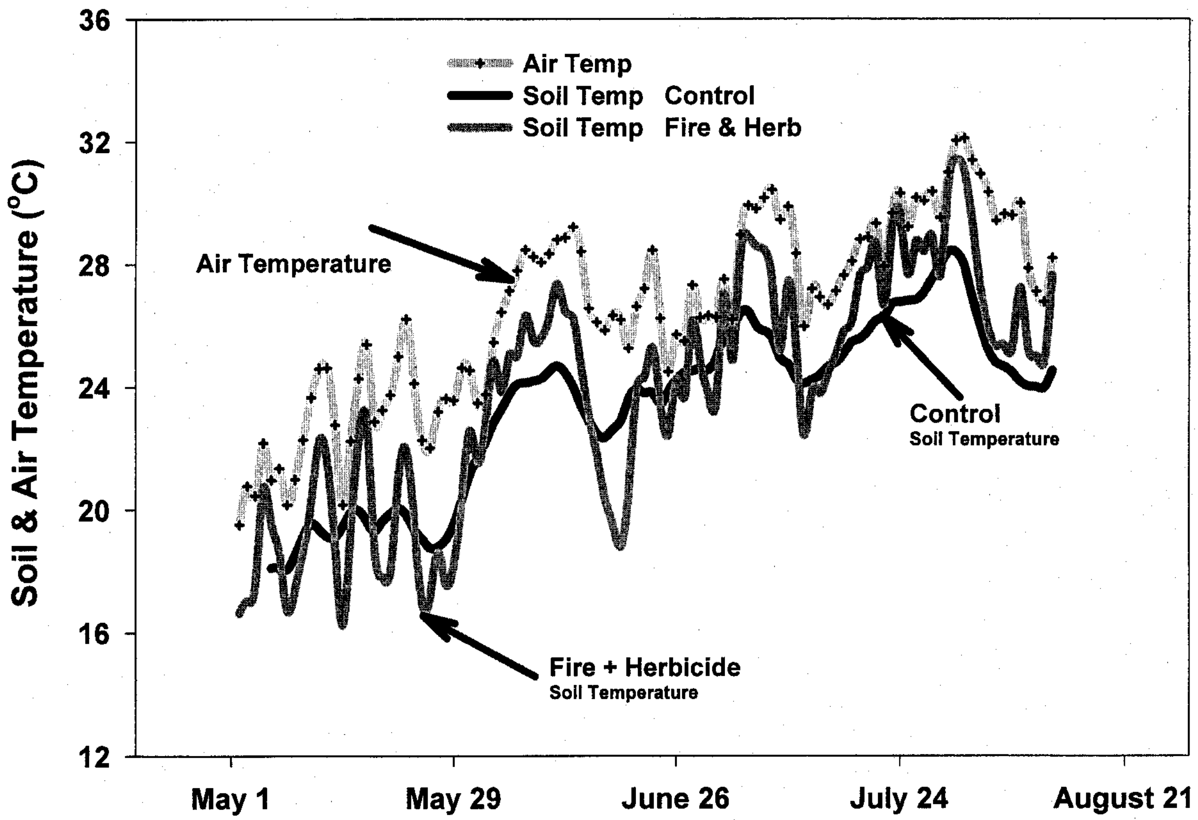

Figure 3. Mean air and soil temperature (5-cm depth) in control and fire-plus-herbicide plots. Daily means were calculated from hourly readings. Air temperature was similar between control and fire-plus-herbicide plots, so an average is presented.

Combined burning and effective chemical removal of tall fescue modified soil climate and affected microbial activity and plant nutrient uptake. At Athey Barrens herbicide more than doubled the extent of bare soil in burned fescue grasslands. Chemical fescue eradication plus combustion of the surface litter layer exposed surface soils to greater heating and drying than fire alone. Although the depressed soil respiration and elevated soil NH_4^+ pool indicated a decline in microbial activity, with adequate moisture during laboratory incubations, soil microbes readily transformed organic N and NH_4^+ in fire plus herbicide plots.

Our work shows that by effectively removing the dominant vegetation, herbicide in combination with fire immediately and dramatically alters the abiotic factors that regulate soil nutrient processes. With time, as warm-season bunchgrasses come to dominate the site, soil nutrient cycling will adjust to species-specific litter characteristics (quality and quantity), rooting patterns, and nutrient uptake. In a Minnesota prairie pure swards

Table 3. Effects of fire and herbicide for tall fescue control on soil acidity, extractable P and cations, and total soil C and N (0- to 10-cm depth).

	pH_{water}	*P*	*K*	*Ca*	*Mg*	*Total C*	*Total N*
		kg/ha	*kmol$_c$/ha*			*t/ha*	
Pre-burn	6.7 ± 0.1	4.6 ± 0.3	4.9 ± 0.1	152.6 ± 5.8	17.8 ± 0.5	23.2 ± 0.4	2.1 ± 0.0
1 day post-burn							
Control	6.6 ± 0.1	4.8 ± 0.4	4.6 ± 0.2	146.6 ± 7.3	16.6 ± 0.6	24.3 ± 0.7	2.3 ± 0.1
Fire	6.6 ± 0.1	4.7 ± 0.3	5.4 ± 0.2	155.7 ± 7.5	18.4 ± 0.6	27.2 ± 0.9	2.5 ± 0.1
4 months post-burn							
Control	6.5 ± 0.2	6.7 ± 0.9	4.5 ± 0.4	105.5 ± 8.0	14.1 ± 0.7	31.4 ± 1.5	2.9 ± 0.2
Herbicide	6.5 ± 0.2	6.0 ± 0.8	4.4 ± 0.3	116.1 ± 8.5	14.3 ± 0.6	30.1 ± 0.9	2.8 ± 0.1
Fire	6.5 ± 0.2	8.1 ± 1.0	4.9 ± 0.3	111.7 ± 9.2	16.0 ± 0.8	32.3 ± 1.3	2.9 ± 0.1
Fire + herbicide	6.6 ± 0.2	9.5 ± 1.4	4.9 ± 0.2	113.0 ± 10.6	14.3 ± 0.9	29.8 ± 2.7	2.8 ± 0.2

Values are means ± SE.

of the native C_4 warm-season grasses *Andropogon gerardi* and *Schizachyrium scoparium* reduced net N mineralization nearly threefold relative to the non-native rhizomatous grasses *Agropyron repens* and *Poa pratensis* within 3 years of establishment (Wedin & Tilman 1990). This species effect on soil N dynamics was attributed to differences in belowground biomass and tissue lignin and N concentrations (Wedin & Pastor 1993). Reduced soil N supply beneath native grasses may confer a competitive advantage to the natives relative to nutrient-demanding invasives such as tall fescue.

At Athey Barrens the rapid transition from continuous fescue sod and litter layer to patchy bunchgrass community suggests that, at least initially, fire-plus-herbicide treatment initiated restoration of community composition and ecosystem structure. Although the increased bare ground in the fire-plus-herbicide plots is typical of native bunchgrass systems, at this point in the restoration process it also increases the risk of reinvasion by tall fescue or other non-native plants. Although further return of the native plant community depends on rapid expansion of warm-season grasses and site recolonization by native forbs, the increased soil N supply may favor high nutrient-demanding non-natives over the native warm-season grasses. Whereas management efforts prioritize non-native species removal to achieve restoration objectives (i.e., establish and maintain species-rich plant community), long-term success in barrens restoration may depend on the degree to which soil conditions, belowground processes, and abiotic conditions favor dominance of native species and resistance to alien reinvasion (Ewel 1987).

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