Sequential Burning Effects on the Soil Chemistry of a Grassland Restoration in the Mid-Atlantic Coastal Plain of the United States

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ABSTRACT

Prescribed burning is a common management tool used in grassland restorations to improve conditions for plant growth. At a grassland restoration in Maryland, we studied the impacts of sequential prescribed burning on near-surface soil chemistry of a highly weathered soil. We hypothesized that soil pH and base cations in the surface soil would increase in the nutrient-poor soils after the burning from char hydrolysis and that cations would be retained in the surface soil between the burns. We collected soil cores 12 days and one year after a fall burn and 12 days after a subsequent spring burn. After the fall burn, we observed that soil pH, extractable cations, and organic matter (OM) were elevated in the soil profile in comparison to soil conditions before initiation of any burning, suggesting an impact of the dissolution of char (the mineral-containing carbonaceous residue of burning), increased root productivity since restoration, and leaching of soluble constituents from aboveground litter in the case of soil K. One year after the second burn, only cations remained elevated. After the third burn, soil pH, OM, Ca, and Mg were greater in the depths below 10 cm in comparison to conditions prior to initiation of burning. We conclude that the net change over time in soil pH, extractable cations, and OM of grassland restorations in the first few years of prescribed burning will depend primarily on the input of new char, the presence of residual char, and the timing and magnitude of leaching events. As the grassland restoration ages, belowground productivity will likely contribute more significantly to changes in soil chemistry.

Keywords: burn, cations, chemistry, grasslands, soil

Although grassland restorations have been ongoing in many regions of the world, few grassland restorations have been developed in the Northeast and the mid-Atlantic regions of the United States (USDA 2008), even though strong evidence exists that grasslands historically persisted for significant periods of time in these regions (Kulikoff 1996, Tyndall 1992). Several restorations in the Northeast have been developed on military grounds, airports, and coastal islands (Vickery and Dunwiddie 1997). In addition, a small number of grasslands are managed at national and state wildlife refuges in the Northeast (Oehler 2003, USFWS 2006). In the mid-Atlantic states, grassland restorations have been primarily conducted on marginal agricultural lands with support by the Conservation Reserve Program (CRP) (USDA 2008). We therefore became interested in participating in a grassland restoration project developed at the Chester River Field Research Center in eastern Maryland in order to investigate changes in the soil chemistry in response to prescribed burning, the primary management tool at the site.

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Soil Chemistry and Grassland Restoration

Most studies of the impact of prescribed burning on grassland restorations focus on changes in above- and belowground productivity. Fewer projects have concentrated on changes in the soil chemistry, such as the concentrations of plant nutrients and soil pH. Moreover, changes in the soil chemistry of restorations undergoing prescribed burning on nutrient-poor, acidic soils common in the Northeast and mid-Atlantic regions would be expected to differ from those developed on the nutrient-rich soils of the Midwest and Great Plains.

Soil Carbon

One of the most common chemical species to monitor in grassland restoration projects is soil carbon (C). Tracking soil C is of particular interest currently owing to the potential for carbon dioxide to be sequestered by plants and stored as soil C to help alleviate global warming (Post and Kwon 2000). Increases in soil C have been reported in grassland restorations on previously cultivated land subjected to frequent prescribed burns, to infrequent burns, or to no burns at all; most are in the last two categories. However, a detailed study was conducted on a chronosequence of grassland restorations in Illinois, ranging from 3 to 26 years in age, all subjected to annual or biennial prescribed burns (Matamala et al. 2008). The investigators discovered an increase in soil C at the restoration sites, with accrual rates increasing with increasing age. They also measured increases in root biomass and a change in the C and nitrogen (N) content of the roots, which would slow decomposition. They attributed the change in soil C to these phenomena. Increases in soil C observed in unburned or infrequently burned grassland restoration chronosequences are also attributed to changes in belowground productivity since restoration (Baer et al. 2002, McLauchlan et al. 2006).

Although loss of aboveground biomass occurs during burning, the Illinois chronosequence study illustrates that even frequent burning can lead to a net gain in soil C in grassland restorations owing to belowground changes in organic matter (OM) cycling. Similarly, in a few native grasslands subjected to long-term sequential burning under longleaf pines (*P. palustris*) in Mississippi (Greene 1935) and in a tallgrass prairie in Kansas (Owensby and Wyrill 1973), increases in organic C were observed and attributed to increased root development in burned fields. On the other hand, losses in soil C have also been detected in some frequently burned native prairies subjected to prescribed burning (Fynn et al. 2003, Ojima 1987, Prober et al. 2008).

Increases in soil C in grassland restorations and contemporary native grasslands that undergo regular prescribed burning are rarely linked to input of combustion by-products of the burn. The combustion residues from burning can range from partly charred plant material to C-rich charcoal, often referred to collectively as black carbon or char (Elmquist et al. 2006). Charcoal and other forms of char have been measured in soils under native prairies that have historically been burned across the United States (Glaser and Amelung 2003, Skjemstad et al. 2002). Laird (2008) estimated that 5%-15% of soil C in Midwestern prairies is charcoal from historic burns. However, only a few contemporary studies of native grasslands subjected to burning link a measured increase in soil C and OM to an input of char from the burns, namely in tobosagrass (*Pleuraphis mutica* [= *Hilaria mutica*]) fields on cracked Vertisols shortly after first-time burning (Ueckert et al. 1978) and on a minimally developed Entisol under native grasses in northern Spain (Ubeda et al. 2005). In grassland restorations, no links between soil C and char have been reported.

Soil pH and Cations

Soil pH and cations have also been monitored in a few grassland restoration projects and in several native grassland studies. Base cations Ca, Mg, and K are important plant nutrients, and soil pH can influence nutrient availability. In those studies in which changes in soil pH and base cations were observed, the mechanism given is related to the char produced from the burns. Although C-rich, the char contains basic salts produced during combustion from inorganic elements in the plant material. These salts can hydrolyze in the presence of water, producing alkalinity, thereby raising the pH and releasing cations into solution (Daubenmire 1968). This is sometimes referred to as the "liming effect" of vegetation burning (Knicker 2007).

Although measurements of pH and cations in the soil of grassland restorations are rare, an increase in soil pH in a grassland restoration subjected to long-term prescribed burning in the northeast of the United States was reported (Niering and Dreyer 1989). In contrast, in unburned or infrequently burned grassland restorations in the Great Plains, no soil pH changes were observed (Baer et al 2002). Soil pH and cation increases have, however, been reported in numerous native prairies under both long-term burning regimes (Ojima 1987, Owensby and Wyrill 1973, Ehrenreich and Aikman 1963) and after first-time burns (Ubeda et al. 2005, Picone et al. 2003). The increases in the soil have been linked to the deposition and subsequent dissolution of char after burns.

Research Objective

Our objective for this study was to evaluate the changes in soil chemistry after a second and third prescribed burn of a grassland restoration site on a weathered Ultisol in Maryland. We postulated that significant changes would be observed as a result of sequential prescribed burning of the grassland owing to the low background soil concentrations of cations and OM of these acidic mid-Atlantic Coastal Plain soils. Shortly after the first prescribed burn of a field at the restoration, soil pH and base cations increased, likely owing to the dissolution of alkaline base-cation-rich char (Sherman et al. 2005). The char from the first burn was 1.12% Ca, 0.17% Mg and 0.24% Na. Soil OM showed minimal changes, however. One year after the burn, soil pH and cations decreased, but not to preburn levels for Ca and Mg.

The initial results from the first burn led us to question whether continued burning would impact the soil chemistry after each burn similarly, or whether any longer-term changes may occur on the highly weathered Coastal Plain soils. We hypothesized that soil pH and base cation concentrations in the surface soil would increase after the second and third burns, as they did after the first burn, and that owing to accumulation on soil cation exchange sites, cation concentrations would remain significantly greater than before burning. We also hypothesized that greater impacts from burning would be observed in the soil after the third burn, which was a spring burn, owing to a greater amount of rainfall typical of spring, in comparison to the second burn, conducted in the fall. On the other hand, since relatively little time had elapsed—three years—since burning began, we did not expect major increases in soil OM, from either incorporation of char from the burns or increases in natural OM from increased root growth.

Study Site History and Description

The grassland restoration was developed at the Chester River Field Research Center (CRFRC) at Chino Farms, located in eastern Maryland (76°01' W, 39°14' N) (Figure 1). The average annual precipitation is 114 cm and the average December and July temperatures are 3.1°C and 25.2°C, respectively (NCDC 2002). Typical of mid-Atlantic Coastal Plain soils, the soil is a highly weathered loam that is acidic and low in OM and major cations (Sherman et al. 2005, USDA 2007).

Chino Farms had been under intensive agricultural production for 50 years prior to establishment of the grassland restoration. The four primary crops were corn (*Zea mays*), wheat (*Triticum aestivum*), barley (*Hordeum vulgare* ssp. *vulgare*), and soybeans (*Glycine max*) (Schwartzman et al. 2002). The farm is owned by a retired physician who is an avid birder. The landowner became interested in reestablishing native habitat for grassland birds on the property, and hence in 1998 he entered 12 low-production agricultural fields (1 to 13 ha) into the Conservation Reserve Program. He invited University of Maryland researchers to develop a grassland restoration on these fields (Schwartzman et al. 2002).

The grassland restoration has been maintained primarily by periodic prescribed burns to remove woody vegetation and enhance growth conditions for the grasses to provide native grassland bird habitat. Five years after seeding the grassland restoration, the grasses successfully covered more than 30 percent of the fields (Gill et al. 2006). Although the original plans were to burn every three years, after the first burn the grassland fields have been burned every 12 to 18 months to remove competing vegetation. Investigators from the University of Maryland have been conducting vegetation and bird studies at the restoration site (Gill et al. 2006).

Methods

In 2003, we began our investigations at a 0.4 ha area in a 13 ha field at the restoration site that had not yet been burned (Sherman et al. 2005). The slope of the field is less than 0.5%. The field had been planted in the spring of 1999 to big bluestem (*Andropogon gerardii*), little bluestem (*Schizachyrium scoparium*), and eastern gamagrass (*Tripsacum dactyloides*) (Schwartzman et al. 2002). As the fields had been in row-crop agriculture for decades, the surface layer of soil had been uniformly tilled across the fields on a regular basis. Preliminary soil studies revealed some variability in soil chemical properties across the field. We determined, however, that the 0.4 ha plot had a similar degree of variability of soil chemical properties, in particular the highly variable soil pH, as well as similar variability in vegetation, to the 13 ha field (Schwartzman et al. 2002, Sherman et al. 2005). Brye and colleagues (2002) used a similar plot size to study the fate of nutrients in litter and char after prescribed burning of a prairie restoration site in Wisconsin.

Prescribed burning of the grassland fields is conducted by the farm manager of Chino Farms. His criteria to conduct the burn is no rainfall for 3–5 days, 25%–50% relative humidity, atmospheric temperature of 2–20°C, and wind speed from 8–24 km/h, not to exceed 40 km/h. Firebreaks are 3–4.5 m wide strips adjacent to the fields. The firebreaks were planted in clover and are mowed regularly. Most commonly, the burns are conducted as backburns; however, headfires are conducted occasionally. The method of burning depends on the number of days since the last rainfall and the wind direction, as well as the desired amount of woody vegetation to remove and the thickness of the duff layer.

The first prescribed burn of the 13 ha field was conducted in April 2003. The second burn was conducted in November 2004 to test the impacts of fall burning on grassland development based on concerns that excess switchgrass (*Panicum virgatum*) growth, which is undesirable for bird habitat, can be promoted by spring burning (Gill et al. 2006). A return to spring burning was implemented in March 2006 for the third burn. The 13 ha field burns in 15 to 30 minutes. Flame heights range from approximately 0.3 m to 12 m, depending primarily on the fuel load. We measured the soil temperature and did not observe any changes in temperature in the surface 10 cm soil. The aboveground temperature during the burn was likely typical of that of grassland burns, in the range 25–50°C (Elmquist et al. 2006, Knicker 2007).

We developed a 25-point sampling grid with points evenly spaced 15 m apart in the 0.4 ha study site. We assumed that samples collected at these points were independent observations characterizing the variability of the site (Sherman et al. 2005). Although soil properties can be spatially correlated, our assumption of independent samples at these distances is supported by other soil studies in native grasslands and grassland restorations (Brye et al. 2002, Brye 2003, Brye et al. 2004b, Brye and Slaton 2003, Brye and West 2005, Brye et al. 2004d). We collected all soil samples from a 0.1 m^2 area at each sampling point within which we assumed soil properties to be uniform (Brye et al. 2002, Sherman et al. 2005).

We collected soil samples from each of the 25 sample points 12 days and one year after the second prescribed burn in November 2004 and 12 days

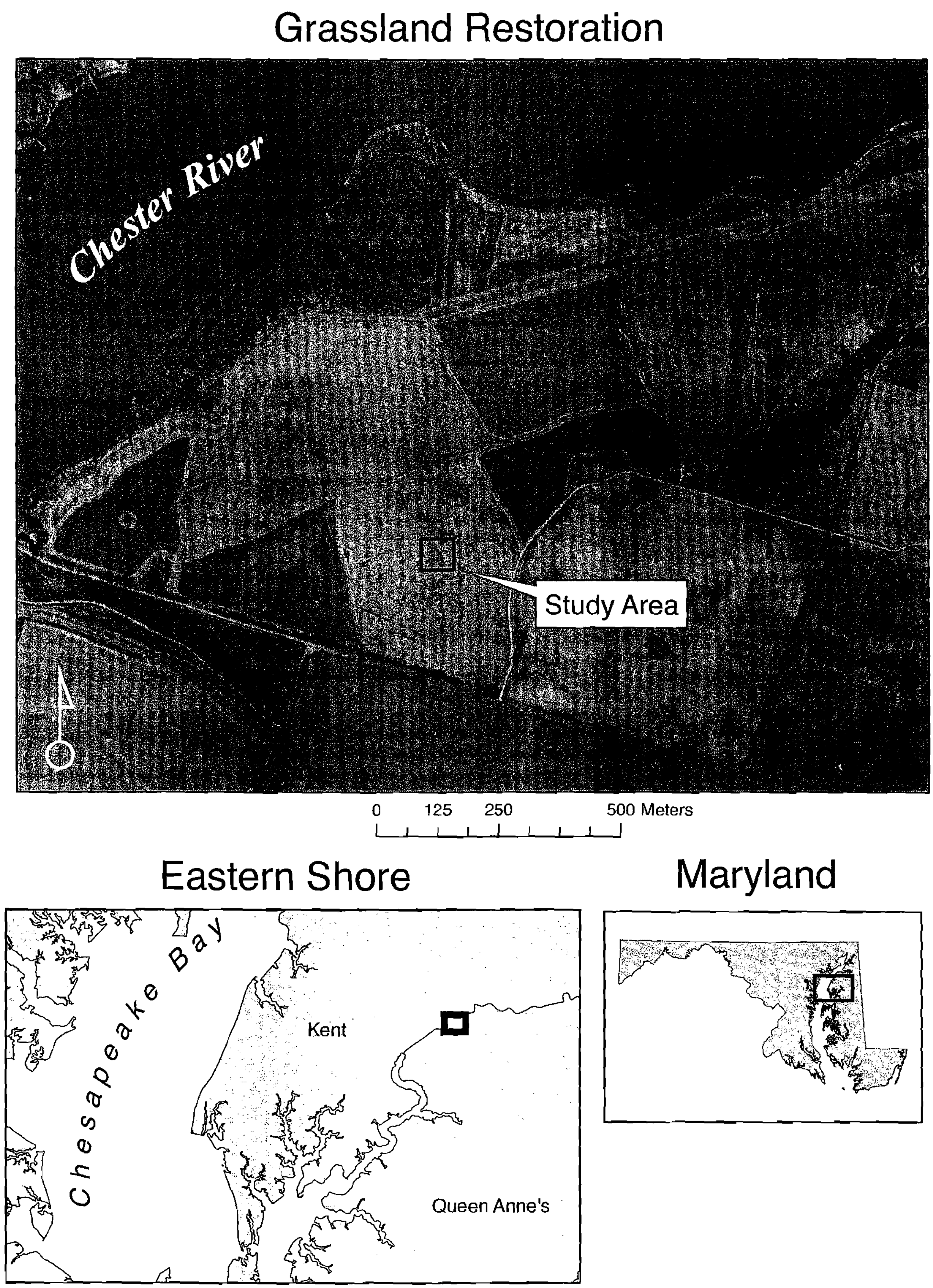

Figure 1. Grassland restoration site at the Chester River Field Research Center at Chino Farms, located in eastern Maryland (76°01' W, 39°14' N). Twelve fields under agricultural production for 50 years were converted to grassland vegetation in 1999. The representative 0.4 ha study site in one of the fields has been studied since 2003.

after the third prescribed burn in March 2006 to investigate the impacts immediately after burning, as well as between burns. Data from the first burn are reported in the journal *Soil Science* (Sherman et al. 2005). We collected samples with a split soil corer, 5 cm in diameter, to a depth of 20 cm and sectioned the cores into five depth intervals to the bottom of the surface soil horizon (0–2.5 cm, > 2.5–5 cm, > 5–10 cm, > 10–15 cm, and > 15–20 cm). At the 12-day sampling after the second burn, we collected only the top three intervals owing to sampling constraints. We analyzed soil from each depth interval in duplicate for soil chemical properties rather than collecting two cores at each site, so as to minimize disturbance of the site over time.

An unburned control area was not a part of the study design, because the primary goal was the restoration of bird habitat (Schwartzman et al. 2002), and without burning, the aboveground biomass becomes too dense for proper bird habitat. We measured soil properties one day before the first burn as the reference point for changes in soil chemical properties after burning (Sherman et al. 2005). The approach of using predisturbance soil properties as the baseline for evaluating postburn disturbance effects has been used previously (Brye et al. 2002, 2003, 2004a 2004c, 2005, Christensen 1976, Sherman et al. 2005, Ubeda et al. 2005). It would be possible to compare postburn data to a neighboring agricultural field, which would be similar to the approach of many CRP soil investigations, but this would complicate interpretation of burning effects owing to other management practices used on the cropland, such as fertilization.

We analyzed duplicate soil samples for pH, OM, and extractable cations. We measured soil pH in 0.01 *M* calcium chloride ($CaCl_2$) (Thomas 1996). To measure soil OM, we used the standard method of loss-on-ignition (LOI) at 400°C (Nelson and Sommers 1996). The measurement includes both natural soil OM and any combustion by-products from the burns that were incorporated into the soil. The combustion by-products from the low-temperature grassland fires will be primarily char, which has been shown to be thermally unstable at 400°C (Elmquist et al. 2006, Nguyen et al. 2004). For extractable soil cations, we performed weak-acid Mehlich-3 extractions, which measure both soluble and exchangeable soil cations (NRCCST 1995). Extracts were analyzed by inductively coupled argon-plasma (ICAP) spectrophotometry (CIROS CCD ICP, Spectro Analytical Instruments, Fitchburg MA). We averaged the results of sample duplicates for statistical analyses.

We determined the homogeneity of variance between sampling dates using Levene's test (Minitab 13.31, Minitab, State College PA). To test for significant changes in average soil chemical properties (n = 25) from one day before the first burn for each of the subsequent burns, we performed a two-sample paired t-test (Minitab) separately by depth. In addition, we performed linear correlations between pH, Ca, Mg, K, and OM with data combined across all depth intervals (Minitab). We then compared the differences in the linear relationships among soil chemical properties pooled across soil depths at each sampling date to the same relationships from 1 day before the first burn using analysis of covariance (SAS vers. 8.1, SAS Institute, Cary NC). Changes in slopes of the linear relationships were considered significant at $p < 0.05$ level.

Results

Soil pH, OM, and extractable cation concentrations in the top 20 cm illustrate that major changes occurred at different depths in the soil profile and to different degrees after each of the burns and between burns. Our results indicate that compositing soil samples across depths should be avoided, as significant changes at various depths may be masked.

Soil pH was elevated 11 days after each of the prescribed burns in comparison to soil pH before initiation of burning (Figure 2). After the first burn, soil pH was elevated at every depth sampled in the top 20 cm of soil (Sherman et al. 2005). However, after the second burn, a significant increase in soil pH was observed only in the top 2.5 cm layer of the surface 10 cm sampled, and this change was slightly smaller magnitude than the change after the first burn. One year after the second burn, soil pH no longer differed from preburn values at any depth sampled, as after the first burn (Sherman et al. 2005). After the third burn, no significant change in soil pH occurred in the surface depths; however, soil pH was elevated in the lower 10–20 cm depths. The increases in soil pH can result from the dissolution of some of the char deposited on the soil surface after the burns, as well as dissolution of residual char incorporated into the soil profile from previous burns.

Extractable soil Ca and Mg also increased after each of the two prescribed burns of the grassland field. After the second burn, soil Ca and Mg increased in the top 10 cm—in the case of Ca, to above the levels after the first burn (Figure 3). By one year after the burn, concentrations decreased in the top 10 cm; however, in the 10–20 cm depth interval, soil Ca and Mg were significantly elevated above values prior to initiation of burning, to a greater degree for Ca than Mg (Figure 4). After the third burn, minor increases in Ca and Mg were measured in all but the top 2 cm layer but did not increase above values measured before the first burn. In the 10–20 cm depth, however, soil Ca and Mg were still significantly elevated above values measured before the first burn (Figures 3 and 4).

The addition of Ca and Mg to the soil profile can occur owing to hydrolysis of the basic salts in the char deposited on the soil surface after the burns. Root decomposition can also be a source. Both Ca and Mg can bind to soil exchange sites, which is a retention mechanism. However, some loss of Ca and Mg between the burns from particular soil layers can be due to plant uptake or leaching of the cations through the soil profile. The net effect after three prescribed burns has been an accumulation of extractable Ca and Mg in the 10–20 cm soil depth at our study site, while a net loss of Mg was observed in the top 5 cm. We had hypothesized that a buildup of Ca and Mg would occur, but did not expect this change to be restricted to the lower depths of the surface soil horizon.

The trends for extractable soil K were quite different from the pattern of soil Ca and Mg changes at the grassland site (Figure 5). Soil K did not increase throughout the profile after the first burn and increased between burns in the surface layers, a trend quite unlike that for Ca and Mg. The increase is particularly pronounced in the top 2.5 cm, where K continued to increase at each sampling period for up to one year after the second burn. The large increase in near-surface K between burns, in contrast to soil pH, Ca, and Mg, suggests that the elevated soil K in the surface layers was due primarily to a phenomenon not directly related to the prescribed burns. Soil K has been shown to be enriched from the decomposition of the standing crop and litter of big bluestem, the primary grass at our field site, in greater amounts than Ca and Mg (Koelling and Kucera 1965, Adams and Wallace 1985, Tukey 1970, White 1973), and K is easily leached from the litter into the soil by rainfall (Whitehead 2000).

Soil OM showed minor changes over the time period studied at the grassland site (Figure 6). Similar to the patterns for soil pH, Ca, and Mg, OM was elevated in the top 10 cm after the second burn, while increases were observed in the lower 10–20 cm depths after the third burn. In contrast, one year after the second burn, soil OM at our site was greater than concentrations before initiation of burning in the 2.5–10 cm layers.

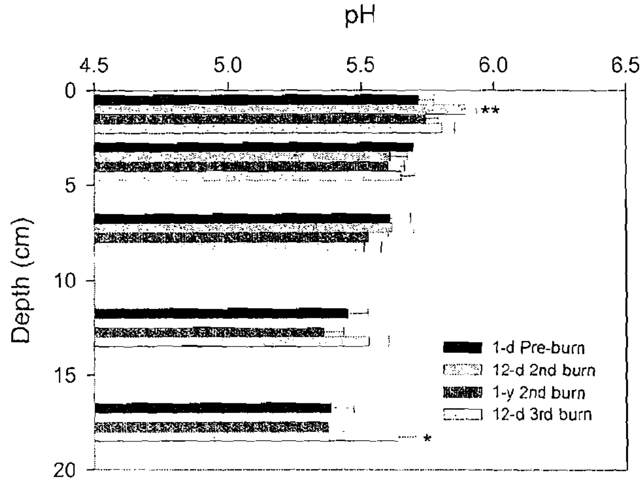

Figure 2. Mean (± SE) soil pH profile ($n = 25$ per depth) one day before the first burn (1-d Pre-burn), twelve days and one year after a second prescribed burn (12-d 2nd burn and 1-y 2nd burn, respectively), and twelve days after a third prescribed burn (12-d 3rd burn). Asterisks denote significant difference from preburn levels at $p < 0.05$ (*) and $p < 0.01$ (**).

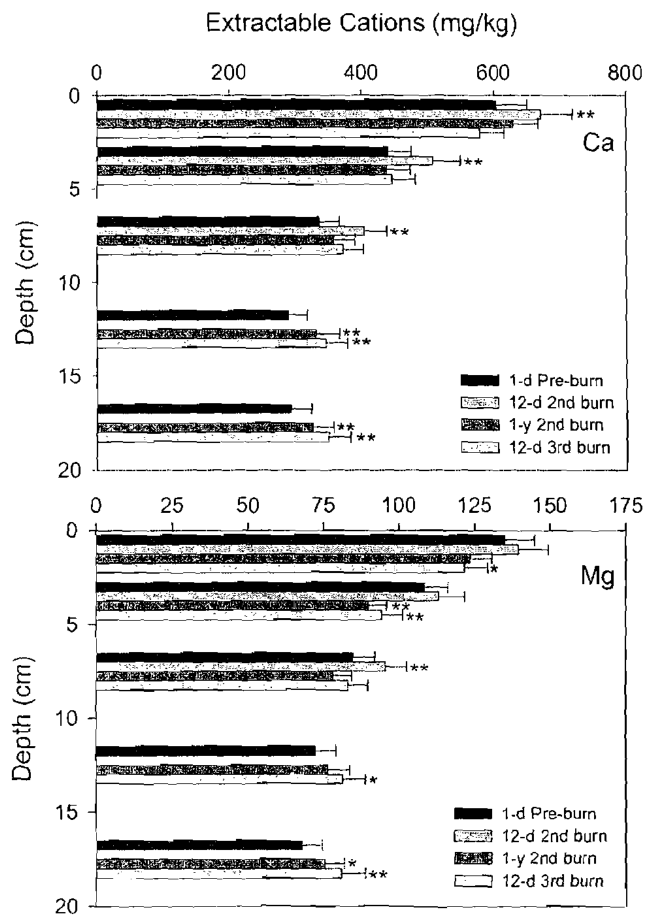

Figure 3. Mean (± SE) extractable soil Ca and Mg profiles ($n = 25$ per depth) one day before the first burn (1-d Pre-burn), twelve days and one year after a second prescribed burn (12-d 2nd burn and 1-y 2nd burn, respectively), and twelve days after a third prescribed burn (12-d 3rd burn). Asterisks denote significant difference from preburn levels at $p < 0.05$ (*) and $p < 0.01$ (**).

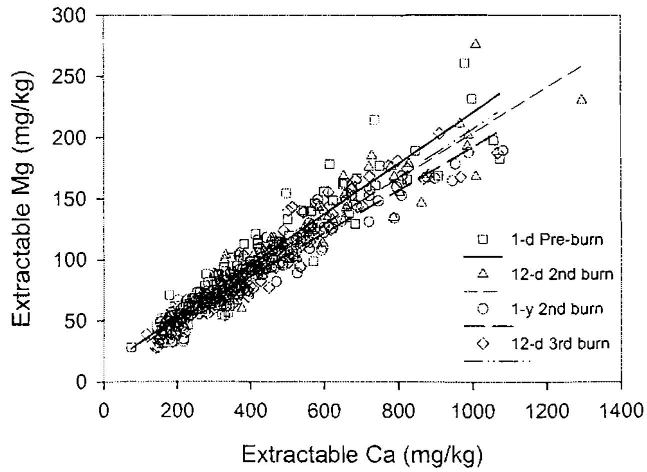

Figure 4. Relationships between extractable Mg and Ca in the top 20 cm one day before the first burn (1-d Pre-burn), twelve days and one year after a second prescribed burn (12-d 2nd burn and 1-y 2nd burn, respectively), and twelve days after a third prescribed burn (12-d 3rd burn). For all dates, $n = 125$, except 12-d 2nd burn when $n = 75$. Bold lines denote a significant decrease in slope from the preburn slope ($p < 0.05$), indicating a greater net gain of soil Ca or a greater net loss in Mg.

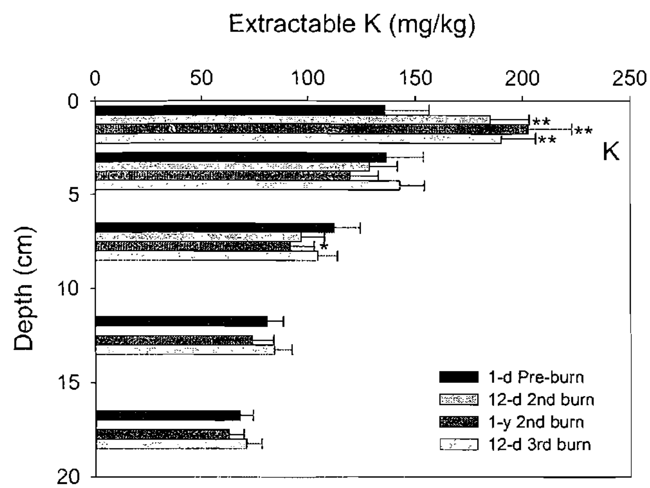

Figure 5. Mean (± SE) extractable soil K profiles ($n = 25$ per depth) one day before the first burn (1-d Pre-burn), twelve days and one year after a second prescribed burn (12-d 2nd burn and 1-y 2nd burn, respectively), and twelve days after a third prescribed burn (12-d 3rd burn). Asterisks denote significant difference from pre-burn levels at $p < 0.05$ (*) and $p < 0.01$ (**).

The OM concentrations were slightly greater than immediately after the second burn in the intermediate 5–10 cm layer, indicating the influence of a source between the burns. Soil C could potentially build up in the soil owing to incorporation of residual combustion products or alteration in OM cycling in the grassland system since conversion from row-crop agriculture.

Discussion

We conclude that changes in soil chemistry at our study site at the grassland restoration are primarily due to the influence of the burning from the char produced and due to natural changes in OM dynamics, both from the change in vegetation from agricultural crops and as a result of the impact of prescribed burning on productivity of the grasses.

The influence of the char on soil chemistry of our site appears to depend primarily on the amount, timing, and duration of the rainfall events after the burns, as well as the fuel load. Table 1 summarizes the rainfall after the three burns (NCDC 2003, 2004, 2006). The pH of rainfall in the region is approximately 4.5 (NADP 2008). After the second burn in the fall of 2004, there was no significant rainfall for eight days, at which time approximately 3.5 cm of rain fell at the study area; no more rainfall occurred before the 12-day postburn sampling. In contrast, rainfall began shortly after the first burn in the spring of 2003, after the burn, occurred over the course of five days, and was of a greater amount; the 4.6 cm of rain was calculated to have penetrated to a depth of 15 cm (Sherman et al. 2005). Only 0.8 cm of rain fell after the third burn and before sampling, and this occurred on the day after the third burn (NCDC 2006). This was the lowest rainfall total after any of the three burns. The patterns of rainfall after the two spring burns were strikingly different in terms of amount and duration, despite the burns being conducted in the same season of the year.

Although no rain fell until 8 days after the second burn, the changes in soil chemistry by 12 days after the second prescribed burn suggest that a significant amount of hydrolysis of salts in the char occurred to raise the soil pH in the top 2.5 cm soil layer. The change in soil pH was likely directly due to the char from the second burn, since the pH had returned to preburn values one year after the first burn. The smaller soil pH change compared to that in the first burn could be due to lower amounts of char produced from only two years of plant growth compared to three years of plant growth prior to the first burn. However, we believe the primary difference was likely the rainfall that occurred after the first spring burn. The greater amount and

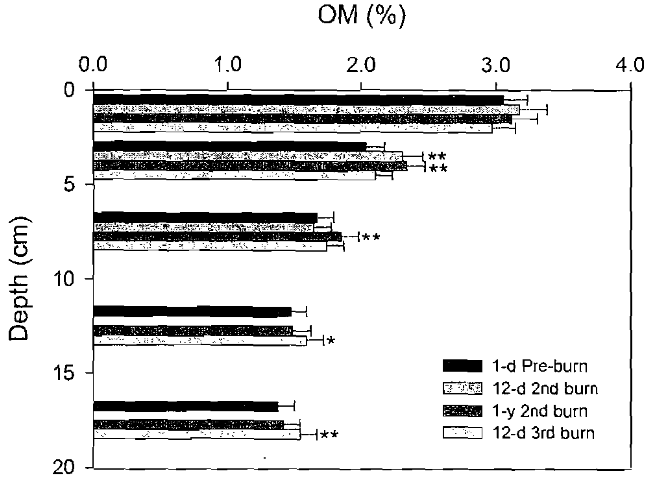

Figure 6. Mean (± SE) soil organic matter (OM) profile ($n = 25$ per depth) one day before the first burn (1-d Pre-burn), twelve days and one year after a second prescribed burn (12-d 2nd burn and 1-y 2nd burn, respectively), and twelve days after a third prescribed burn (12-d 3rd burn). Asterisks denote significant difference from pre-burn levels at $p < 0.05$ (*) and $p < 0.01$ (**).

Table 1. Rainfall in time period between each prescribed burn and postburn sampling 12 days later.

Days after burn	Rain (cm) 1st burn (4-Apr-03)	2nd burn (26-Oct-04)	3rd Burn (1-Mar-06)
1	—	—	0.79
2	—	—	—
3	1.55	trace	—
4	0.03	—	—
5	1.40	—	—
6	—	—	—
7	1.27	—	—
8	0.38	—	—
9	—	3.48	trace
10	—	—	—
11	—	—	trace
Total rainfall:	4.62	3.48	0.79

longer duration of rainfall would have caused more char to infiltrate the soil and undergo hydrolysis after the first burn, as well as minimizing off-track char loss due to wind. The return of the soil pH to preburn conditions one year after the second burn, as occurred one year after the first burn, illustrates again that the alkalinity produced from the char can readily leach from the upper 20 cm of the soil profile, as was observed by Ehrenreich and Aikman (1963) and Ubeda and others (2005) in native prairies.

The extractable cation profiles after the second burn of our restoration site suggest that dissolution of the char also increased Ca and Mg in the surface soil 12 days after the second burn and that some was retained in the soil. Extractable Mg did not change to the same degree as Ca after the second burn (Figures 3 and 4), which is consistent with an approximate sevenfold lower concentration of Mg in the char as compared to Ca. In addition, Ca ions have greater binding affinity to the soil than Mg ions. We observed that extractable Ca concentrations after the second burn were not only greater than before initiation of burning in the top 10 cm, but were greater than concentrations 11 days after the first burn in this region (Sherman et al. 2005). One year after the burn, despite the decrease in Ca and Mg in the upper layers, the elevated Ca and Mg at lower depths support the contention that Ca and Mg are being retained in the soil between burns.

The low rainfall after the third burn would have minimized significant infiltration of new char produced. In addition, the fuel load was lower, since the third burn was of only one season of aboveground growth. Moreover, although seasonal effects of burning on grassland productivity have been shown to be variable owing to controlling factors such as interannual differences in precipitation (Anderson 1990, Glenn-Lewin et al. 1990), spring burns have been shown to result in maximum aboveground productivity of warm-season grasses (Owensby and Anderson 1967, Hulbert 1988). The fuel load for the third burn in spring 2006 was vegetation that grew during the previous summer, which followed the fall 2004 burn and hence was likely a lower fuel load.

The soil profiles after the third burn reveal, however, that the soil can be impacted not only by new char from a burn, but that residual char from previous burns can continue to impact the soil. The significant accumulation of extractable cations and organic matter, and the increase in soil pH in the 10–20 cm layers after the third burn above values measured before initiation of burning, support this contention, as the changes are not likely due to the third burn itself. Enrichment of char C in soil depths below 10 cm has been reported in mixed-grass savannas and native prairies subjected to historic prescribed burning or char addition and has been attributed to downward movement of the char C by soil organisms and with water percolation (Dai et al. 2005, Knicker 2007). Components of char C have been shown to bind to mineral components of soil (Czimczik and Masiello 2007, Knicker 2007, Nguyen et al. 2009), providing a mechanism for soil retention in subsurface soils. Slow dissolution could release soil cations and raise pH at these depths. The net increase in soil Ca and Mg at our site could also occur in part owing to increased root inputs and root turnover from the grasses, as compared to cultivated crop roots; however, these inputs are likely minor in the time frame of the study. Inputs of cations from root decomposition have not been studied significantly in grassland systems, however (Adams and Wallace 1985, Whitehead 2000).

Interpretation of the changes in soil OM observed at our site at the grassland restoration is more complicated, owing to the numerous factors that can impact soil OM dynamics. The slightly elevated soil OM in the top 5 cm after the second burn and in the lower depths after the third burn could be due to incorporated char C from the three burns. Although there was one grassland study in which increased soil OM was ascribed to char infiltration from recent burning, this was due to preferential flow in a Vertisol (Ueckert et al. 1978). Theoretically, char could be retained in the loam soil at our site, as has been reported to occur for char in historically burned prairies (Glaser and Amelung 2003, Laird 2008, Skjemstad et al. 2002) and in the mixed-grass savannas discussed above. The concomitant increases in soil OM, pH, Ca, and Mg after the burns provide support that char was present.

On the other hand, soil OM changes at our site could be due to changes in belowground productivity in the grassland, particularly turnover of a greater root mass of the tallgrass vegetation as compared to the row crops. Increases in soil OM or soil C attributed to changes in root dynamics have been reported in unburned CRP lands after a minimum of five years, attributed to changes in root dynamics, longer than the time lapse of this study (Gebhart et al. 1994, Karlen et al. 1999, Kucharik et al. 2003, Kucharik 2007, Reeder et al. 1998). However, in the CRP chronosequences in the Great Plains (McLauchlan et al. 2006), soil C was found to increase immediately, suggesting that the soil OM increases at our site could be due to increases in natural soil OM from root inputs as well as from char. However, the changes in soil K in the near-surface soil are more clearly related to changes in productivity of the system, likely due to leaching of soluble constituents in the aboveground litter into the surface soil of the grassland.

Conclusions

Whether there will be a net buildup over time in the soil of cations or OM in response to future burning at our grassland restoration site will depend on the net gain from char, as well as changes in the belowground OM dynamics over time. Although observed increases were small after each of three consecutive prescribed burns, the elevated concentrations after each burn in comparison to initial preburn conditions demonstrate the potential for increases in OM and retention of cations, which should positively affect plant growth. As time progresses, natural inputs from increased root production and decomposition and microbial activity will likely contribute more significantly to soil OM and cation concentrations at our site. The results of our study indicate that for grassland restorations in this region, a change can be made to a prescribed burning plan in response to needs to manage the aboveground vegetation, such as the increase in burning frequency at our site to remove excess switchgrass. It appears that the frequency of burning can be increased without negatively affecting soil pH and cation and OM contents, which are all vital to maintaining a successful restoration.

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