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Soil Chemical Responses to Fire Seasonality and Frequency in a Texas Grassland

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ABSTRACT On a clay-loam mixed grassland dominated by honey mesquite (*Prosopis glandulosa* Torr.) in northern Texas, we quantified soil pH, soil organic carbon (OC), electrical conductivity (EC), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), zinc (Zn), iron (Fe), manganese (Mn) and copper (Cu) in response to various effects of summer and winter fire treatments from 1991–1996. We conducted summer fire between August and September, and winter fire between January and March. Treatments that included summer fires increased soil pH, EC, Na, and Cu and temporarily decreased soil OC and Mn ($P \leq 0.05$). The winter fire treatment had a long-term effect of increasing Fe and decreasing Mn. Changes in soil pH were positively correlated with EC, Ca, P and Na, and negatively correlated with K, Fe, Mn, and Zn ($P \leq 0.05$). With the exception of the increases in EC and Na, and temporary loss of OC and Mn, fire treatment regimes that included summer fires did not appear to deplete soil nutrients and may be an acceptable strategy for managing mesquite-dominated grasslands.

KEY WORDS electrical conductivity, fire, macronutrients, micronutrients, organic carbon, prescribed burning, savanna, soil pH

Prescribed burning is usually a beneficial method used in grassland maintenance or restoration that affects the chemical properties of soils. Fire, a vital component of most terrestrial ecosystems, is often utilized to manage woody plant encroachment on grasslands and rangelands (Wright and Bailey 1982), and can modify soil nutrient levels in prairies (Jariel et al. 2004, Jariel Jr. et al. 2010*a*). In the southwestern United States, species such as honey mesquite (*Prosopis glandulosa* Torr.) will sprout from stem bases following fire, and it is necessary to apply repeated burns to maintain suppression (Ansley and Jacoby 1998, Ansley et al. 2006). Thus, there is concern over possible undesirable effects of repeated fires on soil properties (Sharrow and Wright 1977, Brye 2006, Sherman and Brye 2009).

Changes in soil chemical properties and rate of recovery vary widely depending on fire intensity, season of burning (Wells et al. 1979, Romanya et al. 1993), and post-burn length of time (Kutiel et al. 1990, Dormaar and Schaber 1992). While many studies indicate that soil pH and calcium increase, other elements have variable responses following fires (Scotter 1964, Wells et al. 1979, McKee Jr. 1982, Sherman and Brye 2009). While there are numerous studies on the effects of fire on soil macronutrients (Wells 1971, DeBano and Klopatek 1988, Almendros et al. 1990, Weinhold and Klemmedson 1992, Neff et al. 2005), little information is available on the effects on micronutrients (Gonzalez Parra et al. 1996, Brye 2006, Garcia-Marco and Gonzalez-Prieto 2008, Pivello et al. 2010). This paper provides additional information regarding the changes of plant-available macronutrients and micronutrients following fires in Texas grasslands.

Our objective was to determine the effect of repeated seasonal fires on soil pH, soil organic carbon (OC), electrical conductivity (EC), sodium (Na), macronutrients (phosphorus [P], potassium [K], calcium [Ca], and magnesium [Mg]); and micronutrients (zinc [Zn], iron [Fe], manganese [Mn], and copper [Cu]) on a clay-loam mixed prairie mesquite savanna in northern Texas (USA). We hypothesized that repeated summer fires, because of their greater intensity, would affect these soil variables to a greater degree than repeated winter fires. Response to alternate-season fires would be intermediate between repeated summer and repeated winter fires.

STUDY AREA

We conducted our research from 1991 to 1996 on a mixed-grass savanna in north central Texas (34°00’N, 99°20’W). Mean annual precipitation was 665 mm with slightly more than 50% occurring from January to June (360 mm) than July to December (305 mm). Mean annual temperature was 16.9° C and mean monthly temperatures ranged from 3.8° C in January to 29.1° C in July. Soils were fine, mixed thermic Typic Paleustolls of the Tillman series (0–1% slope), which were alluvial clay loams (0 to 3–4 m deep) underlain by Permian sandstone or shale parent material (Koos et al. 1962). Texture was silty clay loam with 32% clay, 52% silt and 16% sand at 0–10 cm depth, and silty clay with 43% clay, 41% silt and 16% sand at 10–20 cm depth. Before burning, the site was dominated by 2–4 m tall honey mesquite at 20–40% canopy cover. Deciduous mesquite trees were full of leaves during summer but without leaves during winter.

Herbaceous understory was a mixture of short and mid-size grasses at roughly equal proportions of cool-season (C_3) and warm-season (C_4) species. Primary C_3 grass species included Texas wintergrass (*Nasella leucotricha*). Dominant C_4 species included buffalograss (*Buchloe dactyloides*) and sand dropseed (*Sporobolus cryptandrus*). Cattle have been

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excluded from the site since 1988. Prior to 1988, cattle were grazed at a moderate continuous level (12 ha per cow) for at least 70 years.

METHODS

Fire Treatments

Our study included three replicate plots of five fire treatments, all on the same soil type and on level surfaces (Table 1). Plot size ranged from 1–6 ha. Fire treatments were (a) an unburned control, (b) three winter fires in 1991, 1993 and 1995 (w91 + w93 + w95), (c) alternate-season fires in winter 1991, summer 1992 and winter 1994 (w91 + s92 + w94), (d) two repeated summer fires in 3 years (s92 + s94), and (e) two consecutive summer fires in successive years (s93 + s94). We conducted winter fires from late January to mid-March and summer fires were from late August through September. We conducted all fires as head fires using methods described by Wright and Bailey (1982). All plots had not been burned for at least 30 yr before this study.

We used fire temperature and intensity measurements to assess fire behavior (Ansley et al. 2006; Table 2). We measured air temperature, relative humidity and wind speed on

Table 1. Fire treatments and number of months between the most recent fire in each fire treatment in mixed-grass savanna in north central Texas, December 1994 and 1996.

	Months after last fire	
Fire treatments[a]	Dec 1994	Dec 1996
Unburned control (U)	0	0
Repeated winter (w91+w93+w95)	22[b]	22
Alternate season (w91+s92+w94)	10	34
Repeated summer (s92+s94)	3	27
Consecutive summer (s93+s94)	3	27

[a] s = summer fire (Aug–Sep); w = winter fire (Jan–Mar); [b] December 1994 samples were collected 22 months after the w93 fire in the winter fire treatment (w95 was implemented in Feb 1995).

Table 2. Weather, herbaceous fine fuel, fire behavior and mesquite response data from each fire "step" (a, b or c) in each repeated fire treatment at the study site in mixed-grass savanna in north central Texas, 1991–1996. Mesquite responses following each fire step are listed, but represent the cumulative effects of repeated fires. All values are means of three plots ± SE. Averages for winter or summer fires over all fire steps are listed on bottom followed by ± standard error (*n* = 15; 3 reps per plot * 5 fires in each season).

Fire treatment[a]	Steps in each fire treatment	Air temp, ° C	Relative humidity, %	Wind speed, $m\ s^{-1}$	Herbaceous fine fuel, $g\ m^{-2}$	Peak fire temp, ° C	Fire intensity, $kW\ m^{-1}$	Mesquite top-kill, %	Mesquite root-kill, %
w91+w93+w95	a. w91	14 ± 3.4	33 ± 8.9	4.5 ± 1.6	235 ± 38	615 ± 5	183 ± 30	11 ± 5.1	2.2 ± 1.7
	b. w93	20 ± 1.2	38 ± 9.5	5.4 ± 1.1	301 ± 10	795 ± 25	6,643 ± 2962	60 ± 3.9	0.9 ± 0.9
	c. w95	25 ± 2.1	26 ± 2.9	4.2 ± 1.6	308 ± 21	581 ± 93	1,236 ± 574	68 ± 6.5	3.7 ± 3.2
w91+s92+w94	a. w91	24 ± 1.6	24 ± 4.1	6.6 ± 1.0	258 ± 8	nd	543 ± 357	30 ± 10.1	0 ± 0
	b. s92	33 ± 0.7	41 ± 3.0	4.6 ± 0.8	429 ± 10	656 ± 39	7,792 ± 961	82 ± 3.2	0.7 ± 0.7
	c. w94	24 ± 0.2	32 ± 2.1	2.5 ± 0.1	130 ± 19	551 ± 79	2,185 ± 1,479	87 ± 7.1	1.4 ± 0.9
s92+s94	a. s92	34 ± 1.0	27 ± 3.8	2.1 ± 0.4	275 ± 54	811 ± 33	3,825 ± 369	93 ± 1.4	0.4 ± 0.4
	b. s94	32 ± 1.1	45 ± 3.3	3.2 ± 0.5	299 ± 31	698 ± 26	2,689 ± 358	92 ± 5.8	2.8 ± 1.6
s93+s94	a. s93	35 ± 0.1	25 ± 0.1	5.6 ± 0.1	240 ± 15	nd	nd	97 ± 0.1	3.3 ± 1.9
	b. s94	33 ± 0.4	47 ± 0.3	4.4 ± 0.3	163 ± 4	571 ± 18	5,327 ± 713	98 ± 0.9	3.7 ± 2.5
Average winter[b]	---	21^{b} ± 1.2	31^{a} ± 1.4	4.6^{a} ± 0.4	247^{b} ± 19	637^{a} ± 28	$2,158^{b}$ ± 677	51^{b} ± 7.8	1.7^{a} ± 0.4
Average summer[b]	---	33^{a} ± 0.3	37^{a} ± 2.7	4.0^{a} ± 0.4	281^{a} ± 25	684^{a} ± 26	$4,908^{a}$ ± 569	92^{a} ± 1.6	2.2^{a} ± 0.4

[a] s = summer fire (Aug–Sep); w = winter fire (Jan–Mar); [b] At $P \leq 0.05$, the difference between average winter and average summer is not significant for each variable with similar letter, but significant for each variable with different letters.

site 5−10 min before each fire. We estimated herbaceous fine fuel amount (litter, grass and forb standing crop) in each plot by harvesting 15 quadrats (0.25 m^2) of herbaceous material in interstitial spaces between mesquite trees. We measured fire temperatures at 1-sec intervals at three to five locations per plot and at four vertical positions (ground level, and 0.1, 0.3, and 1.0 m above ground) per location using thermocouples and a data logger (Model CR7, Campbell Scientific, Logan, UT; Ansley et al. 1998). All thermocouple locations were in grass communities in interstitial spaces between mesquite trees. We estimated flame length by videotaping the flame front as it passed four metal standards in each plot (Ansley et al. 1998). Peak fire temperature was determined in each replicate plot by selecting the highest temperature value that was recorded among all the thermocouples in the plot. Fire intensity (kW m^{-1}) was calculated from flame length measurements using the equation of Byram (1959) and converting to metric units.

Soil Sampling and Analysis

We collected soil samples at 0–10-cm and 10–20-cm depths in December 1994 and December 1996. We collected samples at random within small patches of Texas wintergrass in interstitial spaces positioned between mesquite trees rather than under the tree canopy. We collected 10, 2.5-cm diameter soil cores in each plot and mixed them into two subsamples (five cores per subsample). We oven-dried samples at 65° C for 24 hr, ground them using a soil crusher (Custom Laboratory Equipment Incorporated, Orange City, FL, USA), and passed them through a 1-mm sieve. We weighed and analyzed samples for soil pH and EC of soluble salts using a 1:1 (weight/volume) soil-water ratio. We determined soil OC colorimetrically by wet digestion with 0.5 M $Na_2Cr_2O_7$ (DeBolt 1974). We extracted exchangeable Ca, K, Mg, and Na by 0.025 M H_4EDTA (Texas Agricultural Extension Service 1980) and quantified them by atomic absorption spectrometry. We extracted phosphorus by 0.025 M H_4EDTA and quantified it colorimetrically by developing a blue ammonium-molybdo-phosphate complex (Watanabe and Olsen 1965). We extracted plant available Zn, Fe, Mn, and Cu by diethyl triamine penta-acetate (DTPA) and determined them by atomic absorption spectrometry (Lindsay and Norvell 1978).

Statistical Analyses

We analyzed response of each soil variable using a split-split-plot design with fire treatment as the whole plot, depth as the first split plot, and sample year as the second split plot (three replicate plots per treatment; the two subsamples per plot were averaged prior to statistical analysis). We used the general linear model procedure (Table 3) to determine the probability (*p*) values of soil variables (SAS Institute 2003). We used the replicate (R) × fire treatment (F) mean square as the error term to test effects of fire, the replicate × fire × depth (D) mean square as the error term to test effects of depth and fire × depth, and the pooled error to test effects of year (Y) and interactions of year with fire and depth. With the exception of the repeated winter fire treatment (w91 + w93 + w95), all other fire treatments had a relatively short post-fire interval when sampled in 1994 (3 or 10 months) versus a longer interval (27 or 34 months) in 1996 (Table 1). Thus, we interpreted the effects of year in the model as the combined effects of climatic differences between 1994 and 1996 as well as short-term and long-term responses to fire.

The repeated winter fire treatment was the only treatment that we applied a new fire (w95) to the plots between the

Table 3. General Linear Model procedure analysis and probability (*p*) values of soil variables in response to fire treatment (F), soil depth (D) and sample year (Y) in mixed-grass savanna in north central Texas, 1991–1996. Fire treatments had three replications (R). Source of variation includes main effects (F, D and Y) and their interactions.

Source of variation	Soil properties			Macronutrients					Micronutrients			
	pH	OC	EC	Na	P	K	Ca	Mg	Zn	Fe	Mn	Cu
R	0.46[a]	0.46	0.88	0.10	0.41	0.07	0.70	0.15	0.90	0.08	0.80	0.14
F	*	0.06	*	0.09	0.26	0.05	0.08	0.41	**	**	**	**
D	**	**	**	**	**	**	**	**	**	**	**	**
F × D	0.20	**	0.56	0.09	0.52	**	0.08	0.57	**	*	0.65	**
Y	**	*	**	0.35	0.26	0.49	**	0.16	**	**	0.80	*
Y × F	0.13	**	0.09	*	*	**	0.11	0.50	**	0.07	**	**
Y × D	0.51	0.57	*	0.30	0.61	0.72	*	*	0.65	0.99	0.41	**
Y × F × D	0.43	**	0.54	0.25	0.43	0.77	0.42	0.88	*	0.78	0.58	**

[a] The probability (*p*) values are not significant at $P > 0.05$ (no asterisk), significant at $P \leq 0.05$ (*), and $P \leq 0.01$ (**).

1994 and 1996 sample periods. As a result, the post-fire interval at the time of both the 1994 and 1996 sample periods was 22 months. Inclusion of this treatment in the overall analysis could potentially mask effects of post-fire duration (e.g., “year”) found in other treatments. However, the statistical significance ($P \leq 0.05$) of all factors (including the effect of year) and their interactions was similar with or without the winter treatment in the analysis. Thus, all of our analyses included the repeated winter fire treatment. We separated main effects, two-way and three-way interaction means by LSMEANS at $P \leq 0.05$ (SAS Institute 2003). We determined the linear correlation between two dependent variables (such as between soil pH and each soil variable, and between soil OC and each soil variable) within fire, depth and year treatments (as the overall correlation), within each soil depth and within months after the last fire using Pearson’s correlation coefficients (r; SAS Institute 2003). Based on the value of r that ranges from -1 to $+1$, we tested the significance of r at $\leq$ 0.05 level of significance (Gomez and Gomez 1984).

RESULTS

Fire Behavior

When averaged over all fires, air temperature and herbaceous fine fuel loads were higher ($P \leq 0.01$) in summer than winter fires, but relative humidity, wind speeds and peak fire temperature were similar ($P > 0.05$) in winter and summer fires (Table 2). On average, summer fires burned with more than twice the intensity than winter fires. At least one of the fires within each of the four repeated fire treatments had a fire intensity of >3,800 kW m^{-1}, which was considered a high intensity value for the herbaceous fuel loads available in this mid-grass prairie ecosystem. The net result regarding mesquite responses was that all four repeated fire treatments yielded at least 68% mesquite top-kill and this stimulated grass growth. However, mesquite top-kill was ultimately much greater in fire treatments that included at least one summer fire. Mesquite whole plant mortality was <4% in all treatment groups, and almost all mesquite generated basal sprouting following top-kill (Table 2).

Nutrient Distribution at Soil Depth

All soil variables had significant ($P \leq 0.01$) responses to soil depth, and most soil variables had significant ($P \leq 0.05$) interactions between soil depth and fire treatment or soil depth and sample year (Table 3). When averaged over all fire treatments and sample years, 1.24% OC, 9.1 mg kg^{-1} P, 323 mg kg^{-1} K, 0.33 mg kg^{-1} Zn, 8.9 mg kg^{-1} Fe and 63 mg kg^{-1} Mn were greater at 0–10-cm than 0.94% OC, 6.3 mg kg^{-1} P, 286 mg kg^{-1} K, 0.14 mg kg^{-1} Zn, 5.9 mg kg^{-1} Fe and 48 mg kg^{-1} Mn at 10–20-cm soil depth. The opposite trend was true for the rest of the soil variables with lower responses (pH 7.2, 0.19 dS m^{-1} EC, 1959 mg kg^{-1} Ca, 648 mg kg^{-1} Mg, 20 mg kg^{-1} Na, 0.9 mg kg^{-1} Cu) at 0–10-cm than at 10–20-cm soil depth (pH 7.5, 0.25 dS m^{-1} EC, 2619 mg kg^{-1} Ca, 896 mg kg^{-1} Mg, 54 mg kg^{-1} Na, 1.1 mg kg^{-1} Cu). Relatively immobile elements were concentrated at the surface (0–10 cm), whereas more mobile elements (Ca and Mg) leached into the lower zone (10–20 cm; Table 4).

Soil pH, EC, Na and Macronutrients

Analysis indicated significant ($P \leq 0.05$) main effects of fire treatment, but no significant year × fire or year × fire × depth interaction on soil pH and EC (Table 3). Repeated winter fires, w91 + w93 + w94, did not increase soil pH and EC (Table 5). All treatments that had summer fires (w91 + s92 + w94, s92 + s94, and s93 + s94) increased soil pH by 7% over the control. However, the s92 + s94 fires increased soil EC by 35% over the control. Significant year × depth interactions occurred with EC, Ca, and Mg (Table 3). Soil EC, Ca, and Mg at 0–10-cm depth were not different ($P > 0.05$) between 1994 and 1996, but at 10–20-cm depth they were greater ($P \leq 0.05$) in 1994 than 1996 by 38%, 43%, and 18%, respectively (Table 4).

Table 4. Soil electrical conductivity, calcium and magnesium levels (pooled over fire treatment) in 1994 and 1996 sample years at different soil depths in mixed-grass savanna in north central Texas, 1991–1996. All values are means of three plots. Means are followed by letter(s)[a] and ± standard error.

	EC, dS m^{-1}		Ca, mg kg^{-1}		Mg, mg kg^{-1}	
Depth, cm	1994	1996	1994	1996	1994	1966
0 – 10	0.20^{bc} ± 0.01	0.17^{c} ± 0.01	2,111^{c} ± 103	1,808^{c} ± 77	632^{c} ± 30	663^{c} ± 23
10 – 20	0.29^{a} ± 0.02	0.21^{b} ± 0.01	3,081^{a} ± 211	2,157^{b} ± 105	969^{a} ± 51	824^{b} ± 42

[a] Within a soil chemical property, means with the same letter are not significantly different and means with different letters are significantly different at $P \leq 0.05$ using LSMEANS.

Significant fire × year interactions occurred with K, P, and Na (Table 3, Fig. 1). Soil K at repeated winter fires (w91 + w93 + w95) increased by 22% over the control in 1994 though was similar ($P > 0.05$) to the control in 1996 (Fig. 1A). Soil K at s93 + s94 fire treatment was not different ($P > 0.05$) from the control in 1994, but increased by 27% in 1996, 27 months after the last fire. Soil P at w91 + w93 + w95, s92 + s94 and s93 + s94 fire treatments was at least 100% higher than the control in 1994 (Fig. 1B). By 1996, soil P at s92 + s94 fires was higher ($P \leq 0.05$) than the rest of the fire treatments and the control. In contrast, soil P at w91 + w93 + w95 and s93 + s94 fire treatments decreased to 6.0 mg kg^{-1}, though were similar ($P > 0.05$) to the control. Repeated winter fires increased soil Na by 400% over the control in 1994, but decreased to 28 mg kg^{-1} in 1996 (Fig. 1C). Repeated summer fires (s92 + s94) increased Na also by 400% in 1996.

Soil OC Responses

We documented a significant ($P \leq 0.01$) fire × depth × year interaction for soil OC (Table 3). The alternate season w91 + s92 + w94 fire treatment favored soil OC accumu-

Table 5. Responses of soil pH and electrical conductivity to fire treatments in mixed-grass savanna in north-central Texas, 1991–1996 (pooled over depth and year). All values are means of three plots. Means are followed by letter(s)[a] and ± standard error.

Fire treatments	pH	EC, dS m^{-1}
Unburned control	7.09^{b} ± 0.05	0.19^{bc} ± 0.02
w91 + w93 + w95	7.07^{b} ± 0.08	0.18^{c} ± 0.03
w91 + s92 + w94	7.52^{a} ± 0.09	0.23^{ab} ± 0.02
s92 + s94	7.46^{a} ± 0.07	0.25^{a} ± 0.02
s93 + s94	7.70^{a} ± 0.09	0.24^{ab} ± 0.01

[a] Within a soil chemical property, means with the same letter are not significantly different and means with different letters are significantly different at $P \leq 0.05$ using LSMEANS.

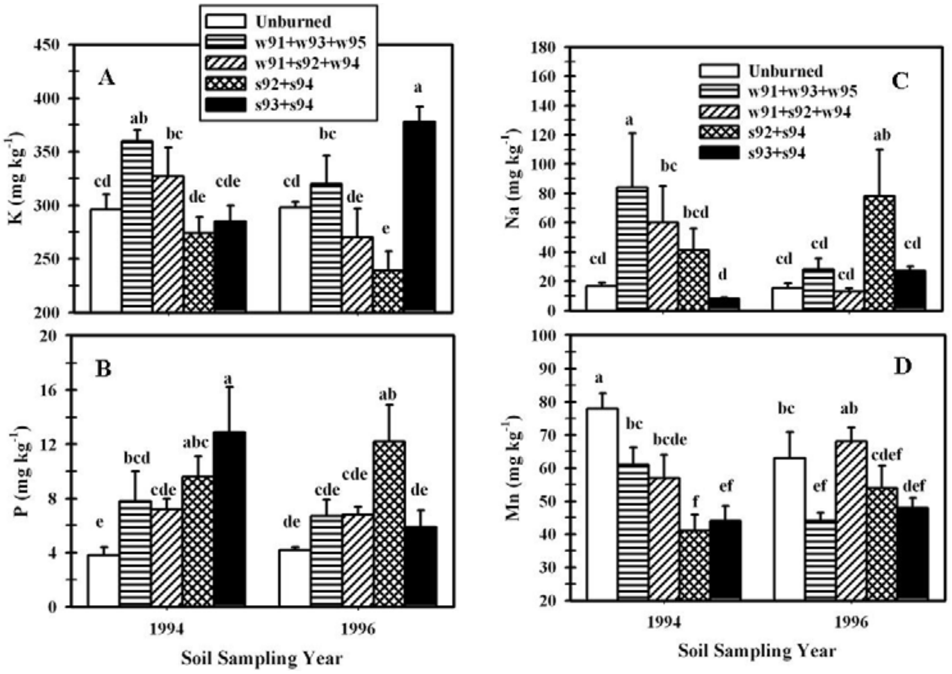

Figure 1. Soil K, P, Na, and Mn in response to fire treatments (unburned control, repeated winter w91 + w93 + w95, alternate season w91 + s92 + w94, repeated summer s92 + s94, consecutive summer s93 + s94) in mixed-grass savanna in north central Texas, 1991–1996. Within each soil element, means (pooled over soil depths) with the same letter are not significantly different ($P \leq 0.05$) using LSMEANS. Vertical lines are standard errors.

lation more than summer fire treatments did (Fig. 2A). At 0–10-cm depth, alternate season fire increased OC by 19% over the control in 1994 (10 months after the last fire) and by 23% in 1996 (34 months after the last fire). Unlike w91 + s92 + w94 fire treatment, repeated s92 + s94 and consecutive s93 + s94 summer fire treatments largely reduced OC by 20% over the control in 1994 (3 months after the last fire). By 1996 at 0–10-cm depth, soil OC increased by an average of 12% (by 16% at s92 + s94 fires and by 9% at s93 + s94 fires over the control, 27 months after the last fire).

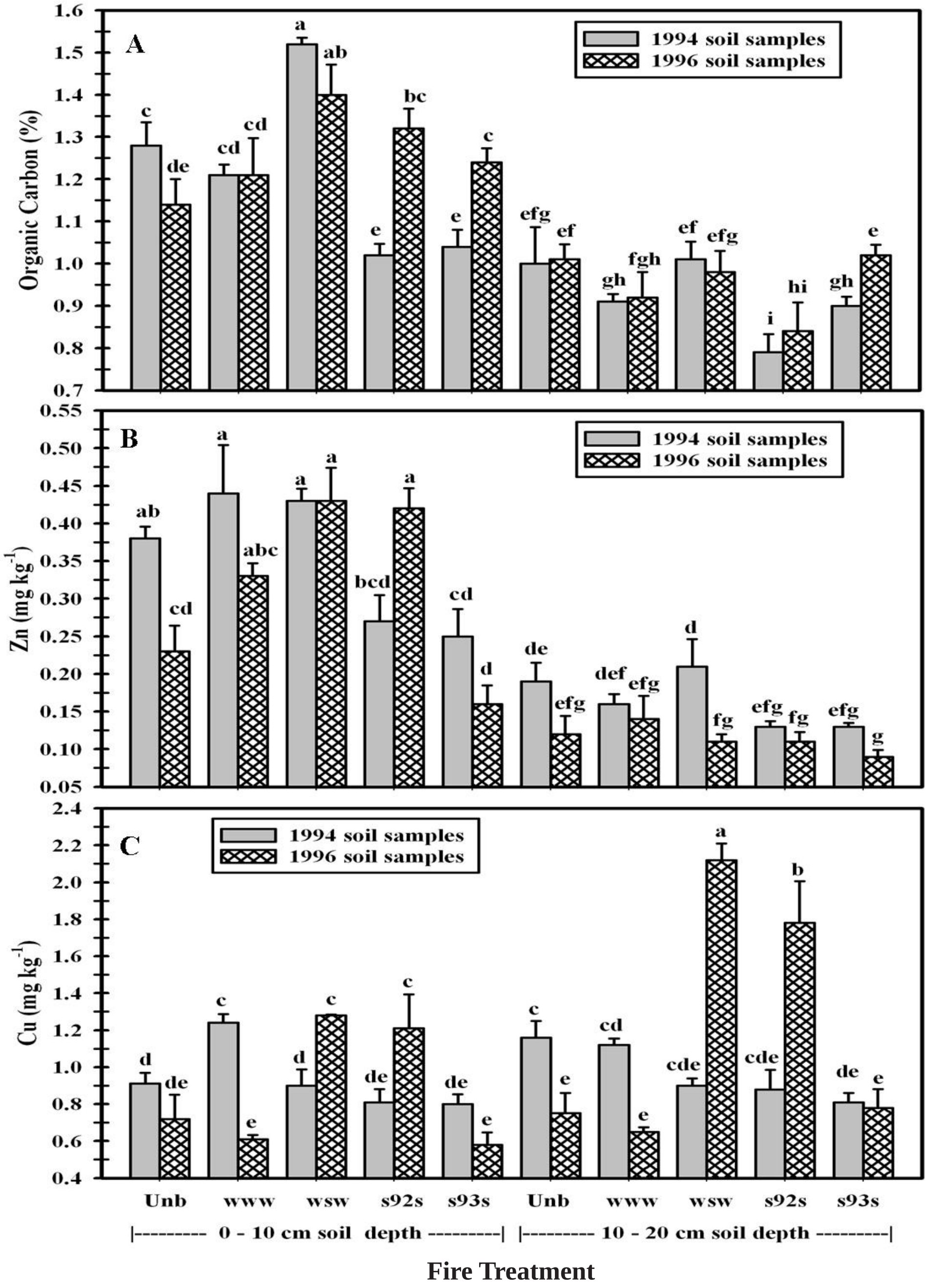

Figure 2. Soil OC, Zn, and Cu in response to soil depths and fire treatments {unburned control (Unb), repeated winter w91 + w93 + w95 (www), alternate season w91 + s92 + w94 (wsw), repeated summer s92 + s94 (s92s), consecutive summer s93 + s94 (s93s)} in mixed-grass savanna in north central Texas, 1991–1996. Within each soil element, means with the same letter are not significantly different ($P \leq 0.05$) using LSMEANS. Vertical lines are standard errors.

Soil Micronutrient Responses

Significant fire × year interactions occurred with Mn (Table 3, Fig. 1D). All fire treatments reduced soil Mn by at least 22% in 1994 relative to the control (Fig. 1D). Both summer fires (s92 + s94 and s93 + s94) decreased soil Mn to a greater degree than did the repeated winter fire (w91 + w93 + w95) treatment. By 1996, soil Mn at repeated winter fires and consecutive summer fires (s93 + s94) remained lower than the control, but Mn at the alternate season fires (w91 + s92 + w95) and the repeated summer fires (s92 + s94) increased to 61 mg kg^{-1} that did not differ ($P > 0.05$) from the control.

We found a significant fire × depth × year interaction for soil Zn ($P \leq 0.05$) and Cu ($P \leq 0.01$) (Table 3, Fig. 2). As supported by significant main effects of soil depth ($P \leq 0.01$), the concentrations of OC (Fig. 2A) and Zn (Fig. 2B) were higher at 0–10-cm than at 10–20-cm depth, but the reverse response was found for Cu (Fig. 2C). Only the consecutive s93 + s94 summer fire treatment reduced soil Zn at 0–10-cm depth in 1994, 3 months after the last fire (Fig. 2B). By 1996, the alternate season w91 + s92 + w94 and repeated summer s92 + s94 fire treatments increased Zn at 0–10-cm, 34 and 27 months, respectively, after the last fire. Soil Zn at 10–20-cm depth was generally unaffected by fire treatments. The repeated winter w91 + w93 + w95 fire treatment increased soil Cu at 0–10-cm depth in 1994, 22 months after the last fire (Fig. 2C). By 1996, the alternate-season w91 + s92 + w94 and repeated summer s92 + s94 fire treatments increased Zn and Cu at 0–10-cm and 10–20-cm soil depths.

Significant fire × depth interactions ($P \leq 0.05$) occurred with Fe (Table 3, Fig. 3). Averaged over year, only the repeated winter w91 + w93 + w95 fire treatment increased soil Fe over the control in both soil depths (Fig. 3), with significantly higher Fe concentrations at 0–10-cm than at 10–20-cm depth. The repeated winter fire treatment increased soil Fe by 100%, while soil Fe under the alternate-season fire and both repeated summer fire treatments were similar ($P \leq 0.05$) to the control (Fig. 3).

Relation of pH to Soil Elements

Overall correlation within fire, depth and year treatments, soil pH had a significant ($P \leq 0.05$) positive overall correlation with EC ($r = 0.67$), Ca ($r = 0.71$), Na ($r = 0.35$), and P ($r = 0.27$), but correlated negatively with OC, K and micronutrients in the order of Fe > Mn > Zn (Table 6). Responses of soil variables by soil depth indicated correlation with pH was different ($P \leq 0.05$) at the two soil depths for most soil variables with stronger correlations at 0–10-cm depth for EC, Ca, Mg, and Fe, and at 10–20-cm for P, K, and Na. All micronutrients were significantly ($P \leq 0.05$) negatively correlated with pH at ≤10 months. Unlike soil pH, OC had a significant

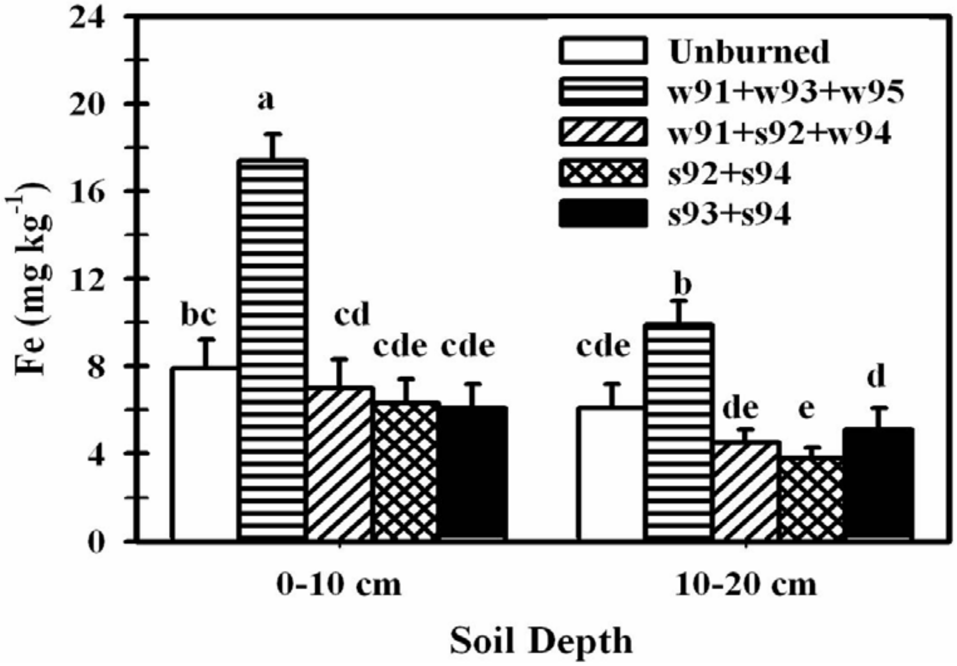

Figure 3. Soil Fe in response to fire treatments (unburned control, repeated winter w91 + w93 + w95, alternate season w91 + s92 + w94, repeated summer s92 + s94, consecutive summer s93+s94) in mixed-grass savanna in north central Texas, 1991–1996. Means (pooled over sample years) with the same letter are not significantly different ($P \leq 0.05$) using LSMEANS. Vertical lines are standard errors.

($P \leq 0.01$) positive overall correlation with Zn ($r = 0.74$), Fe ($r = 0.27$), and Mn ($r = 0.50$; Table 6).

DISCUSSION

Soil pH, EC, Na and Macronutrient Responses

Our results agree, in part, with the literature in that soil pH and EC increased following some of the high intensity fire treatments, but some macronutrients (Ca and Mg) were not affected (Scotter 1964, Pieper et al. 1973, Rashid 1987, Romanya et al. 1993, Pivello et al. 2010). We expected a significant increase in soil Ca following high intensity summer fires relative to unburned control, but this did not occur. While the unburned plots continued to maintain soil Ca by recycling, it is possible that wind speed and Ca uptake by plants contributed, in part, to the lack of increased Ca levels in burned plots. High wind speed of >4 m s^{-1} was sufficient to blow some of the Ca and other nutrients away from the fire treatment plots. Consequently, sudden emergence of new growth after fire may require higher concentrations of Ca relative to other nutrients, because Ca was needed by rapidly dividing cells during germination and establishment (Tisdale et al. 1985).

Frequent cycling of Ca, Mg and Na by annual burning may lead to increased EC and salt toxicity to plants. Soil Ca and Mg contributed to the levels of EC in this soil as they moved from 0–10-cm to 10–20-cm soil depth. Above average 1994 rainfall between the time of the September fires and the December sampling periods may have leached excess Ca and Mg to the lower soil layer. The depletion of Ca and Mg at 10–20-cm in 1996 could be caused by nutrient absorption by plant roots combined with little nutrient deposition on surface soil since the last 1994 summer fires and 1995 winter fire. Soil Na and EC also increased in some treatments that included summer fires. However the combined contribution of Ca, Mg, and Na to EC was not large enough to classify these rangeland soils as saline. The highest EC value in summer fire treatment was 0.25 dS m^{-1}, which was below the threshold value of 1.5 dS m^{-1} for slightly saline soils (Dahnke and Whitney 1988). We did not observe any salinity symptoms on grass plants such as wilting and stunted growth. Thus, the physiological impact of increasing EC from levels in the unburned control (0.19 dS m^{-1}) to that in the

Table 6. Pearson's correlation coefficients (*r*) of soil pH and OC against soil elements at different soil depths and months after the last fire in mixed-grass savanna in north central Texas, 1991–1996.

Soil elements	Overall correlation within fire, depth and year treatments (*n* =60)	Correlation at soil depth 0–10 cm (*n* =30)	Correlation at soil depth 10–20 cm (*n* =30)	Correlation at months after the last fire ≤ 10 (*n* =18)	Correlation at months after the last fire ≥ 27 (*n* =18)
			Soil pH		
OC	–0.29**	–0.06ns[a]	–0.23ns	–0.38**	–0.22ns
EC	0.67**	0.65**	0.60**	0.55**	0.82**
Ca	0.71**	0.81**	0.61**	0.72**	0.64**
Na	0.35**	–0.13ns	0.43*	0.24ns	0.53**
P	0.27*	0.36*	0.56**	0.36*	0.08ns
K	–0.39**	–0.08ns	–0.51**	–0.39*	–0.46*
Mg	0.15ns	–0.41*	<0.01ns	0.01ns	0.36*
Zn	–0.36**	–0.26ns	–0.03ns	–0.54**	–0.27ns
Fe	–0.74**	–0.80**	–0.67**	–0.73**	–0.73**
Mn	–0.63**	–0.41*	–0.71**	–0.87**	–0.34ns
Cu	0.14ns	–0.03ns	0.10ns	–0.58**	0.59**
			Soil OC, %		
Zn	0.74**	0.55**	0.29*	0.81**	0.72**
Fe	0.27**	0.06ns	0.12ns	0.42**	0.21ns
Mn	0.50**	0.35**	0.26*	0.60**	0.42**
Cu	–0.09ns	0.29*	0.08ns	0.02ns	–0.18ns

[a] Correlation coefficient (*r*) is not significant at $P > 0.05$ (ns), significant at $P \leq 0.05$ (*) and ≤ 0.01 (**).

repeated summer fire treatment (0.25 dS m^{-1}) on vegetation was neither damaging nor toxic to the plants in this mixed-grass savanna.

Soil OC Responses

Our study showed that fire treatments had no long-term adverse effects on soil OC. While numerous studies have shown that soil OC has variable responses to repeated fires (Reynolds and Bohning 1956, Almendros et al. 1990, Neff et al. 2005, Sherman and Brye 2009, Jariel Jr. et al. 2010*b*), other studies have documented the recovery of soil OC similar to our results. The recovery of soil OC within 2 yr after the last fire may have been due to greater grass growth in the fire treatments in response to mesquite reduction, or to high precipitation in 1995. Wells et al. (1979) indicated that high intensity fires have greater potential for reducing soil OC. However, Seastedt (1995) suggested that plants responded to high severity fires by allocating more photosynthates toward root growth as an adaptation to the water and nitrogen deficiencies. Our results indicated that soil OC increased in the summer fire treatments, though not in the repeated winter fire treatment, thereby suggesting that the southern mixed prairie system may be dependent on repeated summer-season fires to some degree as a means for accumulating soil organic matter.

Soil Manganese Responses

Responses of soil Mn to fire depend on the form of extractable Mn. Similar to our results, Gonzalez Parra et al. (1996) found that fire decreased exchangeable Mn when extracted by ammonium acetate, NH_4OAc. Conversely, oxidized or reducible Mn (extracted by NH_4OAc-hydroquinone) and total Mn (extracted by HF-HNO_3-$HClO_4$) increased following fire (Gonzalez Parra et al. 1996). The large fraction of total Mn following fire was the reducible rather than exchangeable form. Increases in reducible and total Mn may be due to the contribution of Mn from deposited ash and suggest that Mn does not volatilize at 684° C. Manganese starts to boil and volatilize above 2,061° C (Lide 1991), which rarely occurs in grassfires. In addition, fire may oxidize exchangeable Mn into reducible forms (as oxide/hydroxide precipitates) that are largely unavailable to plants due to lower water solubility (Tisdale et al. 1985, Havlin et al. 1998). Although reducible Mn was not measured in our study, the oxidation of exchangeable Mn into reducible Mn may occur at the same time as the oxidation of carbon atoms from organic matter into carbon dioxide during combustion (Gonzalez Parra et al. 1996). Contrary to our findings, Baldwin and Morse (1994) found that fire increased exchangeable Mn when extracted by sodium acetate. The difference may depend on sodium acetate with NaCl as the extractant. High sodium concentrations may displace Mn from exchange sites, and may also disperse ashes and clay particles to release additional exchangeable Mn. The use of sodium acetate therefore may result in overestimating the actual exchangeable Mn after fire.

Relation of pH to Soil Elements

The significant negative relationship between soil pH and several of the micronutrients suggests that the increase in soil pH, combined with increases in P and Na, was responsible for the decrease in DTPA-extractable micronutrients. Increasing soil pH after burning may induce fixation of Fe, Mn, Cu, and Zn, and decrease their plant-available forms (Tisdale et al. 1985, Sims 1986, Havlin et al. 1998). Iron could be precipitated as hydroxides and occluded in ashes containing $CaCO_3$ compounds, thus decreasing Fe availability in high pH soils. Lowest solubility of $Fe(OH)_3$ occurred at pH 7.4 to 8.5 (Havlin et al. 1998), and interveinal chlorosis in the younger leaves of maize resembling iron deficiency occurred at pH 6.7 (Jariel et al. 1991). Plant available Mn decreased possibly because of the formation of Mn oxides during fire, as well as the formation of Mn hydroxides in high pH soils following fire. Soil pH near or above 7.0 favors the activity of soil microorganisms which could oxidize soluble Mn to insoluble forms (Tisdale et al. 1985, Havlin et al. 1998).

Testing the Summer and Alternate-Season Fire Hypothesis

Summer fires caused a greater increase in soil pH, EC, Na, P and Zn (in 1996) than did winter fires. Repeated winter fires increased soil Fe and decreased soil Mn, while summer fires had no significant effect on these elements at nearly two years post-fire. Thus, our findings support, in part, our hypothesis that repeated summer fires would have a greater affect on soil variables than repeated winter fires. Nutrients may be more concentrated in aerial plant parts during summer due to greater physiological activity than in winter. In addition, greater intensity of summer fires may have caused more complete combustion of organic materials with higher deposition of cations and volatilization of OC. Despite increasing soil pH, EC, and Na and temporarily lowering OC and plant-available Mn, repeated summer fires maintained a non-saline soil condition and did not appear to have any deleterious effects on soils at two years post-fire.

Responses of soil pH, EC, Fe, and Cu (in 1994) and Zn (in 1996) to the alternate-season fire was more similar ($P > 0.05$) to the repeated summer than the repeated winter fire treatment, suggesting that in a fire treatment regime that includes both summer and winter fires, summer fire may have a dominant effect. The large differences in fire intensity recorded in summer fires compared to winter fires may account for this, although variation in peak fire temperature between winter and summer fires was minimal. Thus, our findings provided no empirical support for our hypothesis regarding the intermediate effect of the alternate-season fire.

The two summer fire treatments (s92 + s94, s93 + s94) were expected to have similar effects on soil nutrients, but several differences in nutrient response occurred between these treatments. While both of these summer fire treatments produced high intensity fires of >3,800 kW m^{-1}, consecutive s93 + s94 summer fire treatment altered herbaceous species composition by killing many of the C_4 warm-season grasses and shifting herbaceous composition to C_3 cool-season dominance (Ansley et al. 2006). In contrast, this did not occur in the s92 + s94 treatment.

In the s92 + s94 treatment, after the first fire in September 1992, herbaceous vegetation had two growing seasons (1993, 1994) to recover before the next fire in September 1994. The C_3 grasses recovered rapidly in spring 1993, and C_4 grasses grew rapidly during the 1994 growing season in the absence of mesquite competition and livestock grazing. Thus, by 1994, both C_3 (in spring) and C_4 (in summer) grasses were growing rapidly and extracting soil water and nutrients continuously. A relatively large amount (299 g m^{-1}) of herbaceous material had accumulated at the time of the September 1994 fire, and burning likely deposited a large amount of cations (K, Mg, Na) and increased soil pH from previous s93 + s94 fires. We speculated additional K from ash was likely fixed in 2:1 clay minerals because of the drier soil and the higher soil pH.

In the s93 + s94 treatment, after the 1993 fire, we observed that herbaceous vegetation had less time to recover before the next fire in September 1994. The C_3 grasses recovered during the 1994 growing season, but, as with the s92 + s94 treatment, C_4 grasses did not recover the first growing season following a summer fire. The C_3 plants would have extracted water and nutrients during the spring but were dormant during summer 1994. As a result, less frequent soil drying occurred before the 1994 summer fire in this treatment. Less herbaceous material (163 g m^{-2}) had accumulated by the time of the September 1994 fire, which possibly deposited fewer cations, and soil pH did not increase as much as in the s92 + s94 treatment. Consequently, with lower pH and potentially more soil moisture, we suspected that less K fixation occurred and exchangeable K was higher in s93 + s94 treatment than in the s92 + s94 treatment.

MANAGEMENT IMPLICATIONS

Winter and summer fires employed during our study were of maximum intensity and frequency to be expected for this ecosystem. Repeated summer fires did not appear to have any deleterious effects on soils at two years post-fire. Thus, from a soil nutrient perspective, summer fires appear to be an acceptable strategy for managing mesquite-dominated rangelands. Two summer burns within three to four years may sufficiently suppress mesquite and subsequent burns to maintain suppression could be conducted with lower-intensity winter fires. It should be noted that our study was conducted with livestock grazing excluded and, thus, no additional soil nutrient removal or additions through grazing or waste deposition by livestock occurred. Thus, our results may not apply directly to rangeland management systems that are grazed immediately after fire, because grazing will reduce fuel loads and deplete soil nutrient levels confounded by uneven distribution of deposited nutrients from cattle manure.

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