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REGULAR ARTICLE

Effect of fires on soil nutrient availability in an open savanna in Central Brazil

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Abstract Fire is common in savannas but its effects on soil are poorly understood. We analyzed long-term effects of fire on surface soil of an open Brazilian savanna (*campo sujo*) in plots submitted to different fire regimes during 18 years. The five fire regimes were: unburned, quadrennial fires in middle dry season, and biennial fires in early, middle or late dry season. Soil was collected during the wet and the middle dry season of 2008, and analyzed for pH, organic matter, total N, potential acidity, exchangeable cations and available P, S, Mn, Cu, Zn and Fe. We applied multivariate analysis to search for patterns related to fire regimes, and to local climate, fuel, and fire behavior. Spearman test was used to establish correlations between soil variables and the multivariate analysis gradient structure. Seasonal differences were tested using *t*-test. We found evidence of long-term fire effects: the unburned plot was segregated mainly by lower soil pH; the quadrennial plot was also segregated by lower soil pH and higher amount of exchangeable cations; the time of burning during the dry season in biennial plots did not significantly affect soil availability of nutrients. Differences in elements amounts due to the season of soil sampling (wet or dry) were higher than due to the effect of fires. Higher availability of nutrients in the soil during the wet season was probably related to higher nutrient inputs via rainfall and higher microbial activity.

Keywords Brazilian savanna · Cerrado · Fire · Soil nutrients · Soil properties

Introduction

Fire plays an important role in the development and present day dynamics of Brazilian savanna vegetation, known locally as *cerrado* (Coutinho 1980, 1982, 1990). Primary production and accumulation of nutrients by the ground layer vegetation are affected by fire (Batmanian and Haridasan 1985). However, studies on the effects of fire on cerrado soil properties are few. Noteworthy, amongst the few existing studies are the determination of soil temperatures at different depths during fire (Coutinho 1990; Miranda et al. 1993), the consequences of fire on mineralization of nitrogen and soil microbiota (Nardoto and Bustamante

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2003), the impact of fire on soil water dynamics (Kato and Haridasan 2002; Quesada et al. 2004, 2008), and the relation between woody flora and soil properties subjected to different fire frequencies (Silva and Batalha 2008).

Some general effects of fire on soil chemical, physical and biological properties reported in the literature include changes in soil temperatures and moisture, organic matter consumption, and modifications in soil structure which may lead to changes in water holding capacity and infiltration, and may intensify erosion processes (NWCG 2001; Neary et al. 2005). The ash resulting from the burned vegetation contains basic cations which temporarily increase soil pH, reduce exchangeable Al, and increase availability of nutrients to plants (Allen 1964; Raison 1979; Rundel and Parsons 1984; Coutinho 1990; Pivello and Coutinho 1992; NWCG 2001; Neary et al. 2005). Different results have been reported regarding fire effects on soil microbiota but the majority report significant intensification of bacterial and fungal activity probably due to soil heating, nutrient enrichment, and destruction of toxic substances. Higher incorporation of nitrogen and phosphorus in the soil-plant system may also occur as consequence of microbiota activity (Christensen 1973; Bentivenga and Hetrick 1991; Grasso et al. 1996; NWCG 2001).

Such effects of fires on soil can vary greatly among different ecosystems depending on the severity (a combination of fireline intensity and duration according to Keeley 2009) and frequency of fires. Microbial activity responds to a few degrees of soil heating and the responses can be diverse (NWCG 2001; Erickson and White 2008). Chemical and physical processes that result in soil water repellency may start at about 170°C (Giovannini and Lucchesi 1997; NWCG 2001; Certini 2005; Neary et al. 2005). Volatilization of nitrogen and destruction of organic matter occur above 200°C, but temperatures higher than 760°C are needed to volatilize phosphorus and potassium, and even higher, above 1,000°C, to volatilize calcium and magnesium (Boerner 1982; Wright and Bailey 1982; DeBano 1990). Though the effects tend to be stronger with hotter and longer fires, they are usually limited to the surface layers of the soil (Kennard and Gholz 2001; NWCG 2001; Neary et al. 2005; Knicker 2007).

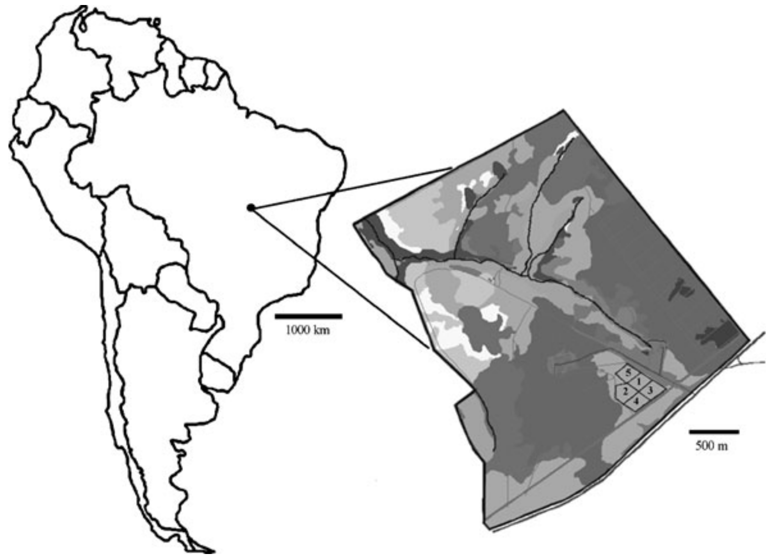
Fires in open savannas are surface fires that rapidly consume the herbaceous biomass and usually do not cause intense soil heating. In open cerrados, Coutinho (1990), Miranda et al. (1993) and Dias et al. (1996) registered temperatures ranging from 74°C to 350°C near soil surface (at depths less than 1 cm) however, the increase in temperature was only a few degrees at lower depths. Fires in the early dry season or a few days after a rainfall are cooler than fires in late dry season (Miranda et al. 1993; Pivello and Norton 1996). Cerrado fires are thus presumed unlikely to cause severe changes in soil physical properties, although Kato and Haridasan (2002) found lower infiltration in frequently burned cerrado soils. In the present study, we intended to search for cumulative effects of 18 years of prescribed fires on the availability of nutrients in the surface (0–10 cm) soil in an open cerrado (campo sujo) in central Brazil. The area, which prior to the experiment was quite homogeneous, was subjected to five different fire regimes (different frequencies and seasons) in a long term ongoing large scale experiment which focuses on changes involving vegetation dynamics and other ecosystem processes due to the periodical fires. We looked for surface soil properties that could be related to fire characteristics such as fire intensity, heat release, soil temperature and duration of high air temperatures. Our working hypothesis assumed that different fire regimes could produce different patterns of nutrient availability in the surface soil. As the experimental design of the original project is unreplicated, we could not test treatments *a priori*, and thus our intention was to look for patterns *a posteriori*.

Materials and methods

Study area

The study was conducted at the Ecological Reserve of the Brazilian Institute of Geography and Statistics (IBGE), 35 km south of Brasilia (15°56′S–47°52′W) (Fig. 1). The reserve covers about 1,300 ha with altitudes ranging from 1,048 to 1,150 m. The climate is tropical with wet hot summers and dry mild winters (Koeppen's Cwa). Mean annual rainfall is 1,453 mm, of which 75% occur from October–November to April–May (IBGE 2004). Relief is flat to gently rolling. The geology reveals very old Pre-Cambrian rocks and also more recent Tertiary and Quaternary rocks. Tertiary lateritic terrains occupy most of the Reserve and gave origin to very deep well-drained

Fig. 1 Location of the plots of the long-term experiment on fire regimes at the Ecological Reserve of IBGE, Brasília, DF, Brazil, 15°56′S–47°52′W. (*1* = biennial fire, early dry season; *2* = biennial fire, middle dry season; *3* = biennial fire, late dry season; *4* = quadrennial fire, middle dry season; *5* = unburned)



yellowish Oxisols with a clay texture–which covers about 80% of the Reserve—and also to Cambisol and concretious Plintosol; Quaternary terrains are mainly associated with the drainage system and hydromorphic soils (IBGE 2004; Quesada et al. 2004). According to Kato and Haridasan (2002) and Haridasan (1994), soil in the experiment plots can be described as clayey Latosol at all depths (clay content from 508 to 746 g kg^{-1}). The bulk density varied from 0.72 to 0.90 g cm^{-3}, usually lower at surface, and the total porosity varied from 68% to 73%. Vegetation consists of a mosaic of different *cerrado* physiognomies, from dense to open savannas, and some forest physiognomies (IBGE 2004). In 1994, 2 years after the first prescribed fires in the biennial plots, Andrade (1998) reported that there were no significant differences in both the fine fuel load and species composition between the unburned plot and the three biennial fire plots. Today, woody elements are more abundant in the unburned plot as a result of fire protection since 1974.

Fire data

In 1990, a long-term research project was established to investigate the effects of different regimes of prescribed fires on the cerrado vegetation. At that time the vegetation was protected from fire for 16 years. One set of five 200×200 m plots was established in an open savanna physiognomy (*campo sujo)* where one of five fire regimes was allotted to each plot. The fire regimes included unburned (control), fire once every 4 years (quadrennial fires) during the middle of the dry season, and fire once every 2 years (biennial fires) in early, middle or late dry season (Fig. 1). Details of this experiment can be consulted in Gonzales et al. (1997) and RECOR (2002a). From 1992, when the prescribed fires started, to 2008, when the present study began, the quadrennial plot was burned 5 times and the biennial plots 9 times.

The prescribed biennial fires of 2008 were carried out in June, August and September and fire characteristics were recorded using the same methodology employed from 1992 to 2000 (H.S. Miranda, unpublished data). Air temperatures were recorded with chromel-alumel thermocouples (32 swg) at 1, 60 and 160 cm above soil surface at one-second intervals, using Campbell 21X data logger. Soil temperature at 1 cm below soil surface was recorded at 2 min-intervals. To estimate fuel consumption, 10 samples (50 ×50 cm) of fine fuel were collected at random immediately before and after the fires. Fuel was separated into live graminoids, dead or dormant graminoids, live dicotyledons, and dead dicotyledons. The fireline intensity (Byram 1959) was calculated considering the heat yield of 15,500 kJ kg^{-1} recorded for other savannas (Griffin and Friedel 1984).

Heat release per unit area was calculated from fireline intensity (Luke and McArthur 1978; Rothermel and Deeming 1980).

The average maximum temperature for the month of fire, total precipitation, and water stored in soil during 2 months before the fire for all the prescribed fires during the experiment were obtained from EMBRAPA (2002–2009). The parameter values relative to all fires were grouped, and principal component analysis (PCA) was conducted to verify the existence of correlations between the burning season and fire behavior, and between fuel characteristics and local climate.

Sampling design and data analysis

To search for possible cumulative effects of the repeated prescribed fires on availability of nutrients in the soil, 24 samples were collected randomly from the top 10 cm in each plot in the wet season (February) and 48 soil samples in the dry season (July) of 2008 for chemical analyses. Surface soil was chosen both because fire effects are expected to be more evident at surface and because stronger association between vegetation and soil properties occurs at surface (Ruggiero et al. 2002). We did not collect soil from the biennial early dry season fire plot in the dry season because of the short interval after the preceding fire of June 2008, since the main objective of this study was to evaluate long-term and not immediate fire effects.

Soil samples were air dried, sieved (2 mm) and analyzed in the Soil Laboratory of Centro de Energia Nuclear na Agricultura, Piracicaba, SP, for pH, organic matter content, total N, potential acidity (Al+H), exchangeable cations, and available P, Fe, Cu, Zn, Mn and S. Soil pH was determined in 0.01 M $CaCl_2$ solution using an electronic pH meter. The organic matter content was determined by colorimetry after wet combustion using modified Walkley-Black method (Walkley and Black 1934). Total N was determined by the microkjeldahl method (Camargo et al. 1986; Raij et al. 2001). Potential acidity was determined potentiometrically in SMP buffer solution (Raij et al. 2001). Exchangeable cations, K, Ca and Mg, and available P were extracted using ion exchange resin. Potassium in the extract was determined by atomic emission photometry, Ca and Mg by atomic absorption spectrometry, and P by colorimetry (Camargo et al. 1986; Raij et al. 2001). Micronutrients, Fe, Cu, Zn and Mn, were extracted with DTPA solution and determined by atomic absorption spectrometry (Lindsay and Norvell 1978). Sulphur (S-SO_4) was extracted with 0.15% $CaCl_2$ solution and determined by turbidimetry using barium sulphate (Vitti 1989). Cations exchange capacity and the sum of bases was determined according to EMBRAPA (1998).

We calculated means and standard deviations for different fire regimes and searched for patterns in soil data using multivariate exploratory techniques. A gradient analysis procedure based on principal coordinates analysis (PCoA) was performed on a between-samples distance matrix calculated with the Gower General Similarity Coefficient (Legendre and Legendre 1998). The PCoA matrix included data on soil pH, organic matter, potential acidity, P, N, K, Ca, Mg, Fe, Cu, Zn, Mn, and S of all fire regimes. We chose to use the exchangeable cations, K, Ca and Mg individually, instead of the sum of bases, in the analyses to avoid missing any information that each element could provide. Matrix values were standardized by the ranging method prior to the PCoA procedure (Legendre and Legendre 1998). The sample scores on the two first axes were explored for depiction of patterns related to differences among burning plots. The correlation between soil variables and gradient structure was explored using Spearman correlation coefficient, where the samples scores were correlated with each soil variable. Only correlations at two-tail level of significance ($\alpha <$ 0.01) were considered. The segregation of plot mean scores on the two first axes of the PCoA was evaluated using a multivariate analysis of variance (MANOVA) model with five independent categorical classes, corresponding to the different fire regimes and scores on the two first axes as dependent variables (Legendre and Legendre 1998). Tukey multiple comparisons test was performed to detect the differences among plots. To compare means for the two sampling dates we applied a t-test (Zar 1999). Statistical analyses were performed using the softwares SPSS (SPSS Inc. 2001), SYSTAT (SYSTAT Inc. 1992) and PAST (Hammer et al. 2001).

Results

Data from the 2008 fires showed a high proportion of grasses in the fine fuel which dries out, becoming dead or dormant as the dry season progresses (middle and late dry season, Table 1). Independent of the season, more than 90% of the fine fuel was consumed (Table 1)

Table 1 Fine fuel composition at the time of prescribed fires in early, middle and late dry season of 2008 in the experimental plots at the IBGE Ecological Reserve (Brasília, DF, Brazil)

Fuel component	Season		
	Early dry	Middle dry	Late dry
	Composition (%)		
Live graminoids	16	5	7
Dead or dormant graminoids	29	59	55
Live dicotyledonous	35	27	28
Dead dicotyledonous	20	9	10
Consumed during fire (%)	92	96	97

with amounts ranging from 4.9 to 9.4 Mg ha^{-1} (Table 2). Maximum air temperatures were usually higher in middle and late dry season, especially at 60 cm (Table 2). Temperatures higher than 60°C lasted only a few minutes. Fireline intensity varied from 1,256 to 20,392 $kJ.m^{-1}.s^{-1}$; maximum values were due to high rates of fire spread (Table 2). Although there was a large variation in fireline intensity, the heat released per unit area was more homogeneous among the fires, around 9,610 $kJ.m^{-2}$ (Table 2). Belowground, at 1 cm depth, soil temperatures increased only 6.7°C during middle dry season fire and 5.7°C during late dry season fire in 2008 (Table 3).

The first two axes of the PCA considering fire season, fire behavior and climate parameters accounted for 57% of the variation (Fig. 2). Air temperature at 1, 60 and 160 cm were very correlated to each other (Fig. 2). Biennial middle dry season and quadrennial fires were hotter compared to most biennial early dry season and some biennial late dry season fires which were associated with higher environmental humidity due to previous rainfall and higher amount of water in the soil (Fig. 2). Higher fireline intensity and fire spread were associated with higher air temperatures during the month of fire (Fig. 2).

The soil of the experimental plots was acid with pH below 4.5 and potential acidity above 70% (Table 4). The soil had less than 5.5% organic matter content and the availability of major plant nutrients was low, exhibiting large variations. Most of the soil variables showed significant differences ($p<0.001$) between wet and dry season for the unburned, biennial middle dry season and quadrennial fire regimes. The availability of nutrients was generally higher during the wet season (Table 4).

The two first axes resulting from the PCoA performed with the wet season data represented 26.6% of the matrix structure, with the fist axis accounting for 15.2%, and the second axis 11.4%. Consistent differences existed among fire treatments. This analysis showed a clear segregation of the unburned plot both along the first axis and the second axis (Fig. 3a and b). The second axis also segregated biennial late dry season and quadrennial fire regimes (Fig. 3a and b). The MANOVA showed significant segregation of fire regimes along both axes (axis 1: $F=5.8$, $p<0.001$; axis 2: $F=36.4$, $p<0.001$) and the Tukey test showed the significant differences among fire regimes. The unburned plot was segregated along the first and second axes (Fig. 3a and b). Quadrennial plot was segregated along the second axis (Fig. 3b). Biennial fire plots showed similarity in the first axis (Fig. 3a) but biennial early dry season plot was different from biennial middle dry season plot in the second axis (Fig. 3b). Significant correlations among the axes scores and the soil variables were corroborated by the Spearman correlation analysis (Table 5). Along the first axis, pH was separated from the all other variables and along the second axis, pH + Mn + the soil bases (K, Ca and Mg) were segregated from potential acidity, S and Zn (Table 5; Fig. 3a and b).

The PCoA using dry season soil data showed that the first axis represented 18.0% of the matrix structure, and the second 11.1%. This analysis also resulted in the segregation of both unburned and quadrennial regimes along the first axis, and of biennial late dry season fire regimes along the second axis (Fig. 3c and d). Significant segregation was shown by MANOVA (axis 1: $F=20.9$, $p<0.001$; axis 2: $F=36.608$, $p<0.001$). Tukey test showed significant differences among three groups along the first axis: (1) unburned, (2) quadrennial and (3) biennial middle dry season and biennial late dry season (Fig. 3c). Along the second axis, three groups were separated: (1) unburned and quadrennial,

Table 2 Maximum air temperature at different heights and fire parameters during prescribed fires from 1992 to 2000 in the experimental plots at the IBGE Ecological Reserve (Brasília, DF, Brazil)

Fire regime year of burning	Years without fire	Max. air temperature (°C)			Rate of spread m s^{-1}	Fireline intensity kJ.m^{-1}.s^{-1}	Heat released kJ.m^{-2}	Fuel consumption Mg ha^{-1}
		1 cm	60 cm	160 cm				
Biennial								
Early dry season								
1992	18	633	327	230	0.3	3013	11160	7.8
1996	2	768	873	755	0.3	2926	9145	6.0
1998	2	–	–	–	0.5	6361	11789	7.9
2000	2	145	325	211	0.4	3819	8680	5.7
2008	2	359	542	–	0.2	1597	7985	5.6
Middle dry season								
1992	18	672	713	700	0.1	1390	10695	7.2
1996	2	534	577	477	1.4	20392	14260	9.4
1998	2	592	425	331	1.0	7804	8215	5.7
2000	2	577	–	757	0.2	1442	9610	5.5
2008	2	596	641	581	0.3	2187	7291	4.9
Late dry season								
1992	18	481	412	320	0.2	1256	8370	6.4
1996	2	423	743	482	0.4	6138	13950	9.1
1998	2	349	509	330	0.5	5425	10850	7.2
2000	2	259	538	412	0.3	3632	11005	7.2
2008	2	562	765	580	1.5	12404	8269	5.5
Quadrennial								
1995	4	768	755	601	1.0	9455	9455	6.5
1999	4	518	876	651	0.4	3466	8060	5.3
Minimum		145	325	211	0.1	1256	7291	4.9
Maximum		768	876	757	1.5	20392	14260	9.4
Median		534	566	477	0.3	3632	9610	6.4

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and (2) biennial late dry season and (3) biennial middle dry season (Fig. 3d). Spearman correlation analysis also showed significant correlations among the axes scores and the soil variables (Table 5). As in the case of wet season data, the first axis put pH apart from all other significant variables and the second axis separated pH + Ca + Mg + S + Cu + Mn + Zn from P + potential acidity (Table 5; Fig. 3c and d).

Table 3 Air and soil temperatures during prescribed fires of 2008 in the experimental plots at the IBGE Ecological Reserve (Brasília, DF, Brazil)

	Early dry season	Middle dry season	Late dry season
Duration of air temperature >60°C (seconds)			
1 cm above soil surface	72	231	272
60 cm above soil surface	129	111	86
Maximum soil temperature (°C at 1 cm depth)	–	31.8	31.2
Increase in soil temperature (°C)	–	6.7	5.7

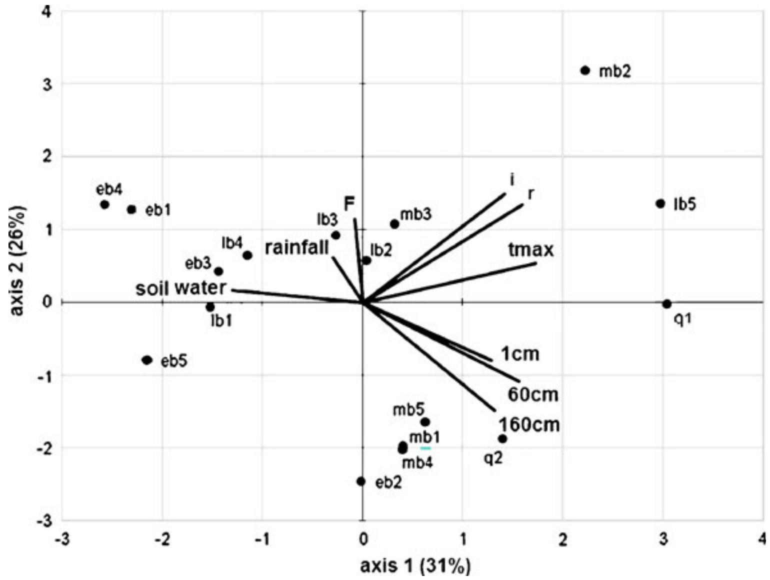

Fig. 2 Biplot diagram of the Principal Component Analysis (PCA) using data of average maximum air temperature from the month of fire (*tmax*), rainfall, water stored in soil 2 months before the fire (*soil water*), the amount of fuel consumed in the fire (*F*), and air temperatures at 1, 60 and 160 cm, fireline intensity (*i*), rate of fire spread (*r*) during fires as related to five biennial early dry season fires (*eb*), five biennial middle dry season fires (*mb*), five biennial late dry season fires (*lb*), and two quadrennial fires (*q*) in an open savanna

The comparison between wet and dry seasons data showed significant differences ($p<0.01$) for most of the soil chemical variables in the biennial middle dry season, unburned and quadrennial plots (except for K, Cu and Fe in middle dry season; pH, potential acidity and K in unburned plot, and potential acidity, P, S and Fe in quadrennial plot) (Table 6). Biennial late dry season plot showed higher similarity between seasons. The variables organic matter, N and Mn were significantly different in all plots and none of the chemical variables were similar in all plots (Table 6). In spite of the dissimilarity between seasons, there was a constant trend of higher values for all variables (except for potential acidity) in the wet season samples (Table 6).

Discussion

As in most tropical savannas, the fires in open savanna at the Ecological Reserve of IBGE were typically surface head fires that quickly consumed the herbaceous layer, composed mostly of grasses, and not very hot as compared to other fire prone ecosystems (Gillon 1983; Frost and Robertson 1987; Whelan 1995; Trollope et al. 2002; Gill et al. 2009; Miranda et al. 2009). The values of fine fuel load, fuel consumption, maximum air temperature, fireline intensity, fire spread rate, and heat released per area were in the range observed for other open physiognomies of cerrado (Coutinho 1990; Kauffman et al. 1994; Castro and Kauffmann 1998; Miranda et al. 1993, 2002, 2009; Krug et al. 2002). Fuel consumption by fire varied from 92% in biennial early dry season fires to 97% in biennial early dry season fires (Table 1), and very similar values of fuel consumption were obtained in previous prescribed fires in the same area, independently of the burning season (Kauffman et al. 1994; Castro and Kauffmann 1998; Miranda et al. 2002; Krug et al. 2002). Even being the temperatures in open cerrado fires relatively low if compared to other ecosystems, fuel consumption is high because most fuel is fine and composed by grass leaves (Miranda et al. 2009). A higher variation in fireline intensity was a consequence of different rates of fire spread and amounts of fuel consumed. High rates of fire spread recorded in August and September may be due to high wind speed at the time of fires, typical of these months in the region (Almeida 1995; RECOR 2002b)

Results of PCA using fire characteristics and climate parameters basically indicated the variation in fire behavior according to fuel load and dryness of the environment, which are influenced by season of fires. Thus, the influence of climatic conditions on fire behavior occurred on different time scales: (1) conditions at the time of fire, and (2) conditions over a longer period preceding the fire. Fire behavior was not affected by the frequency of fires since quadrennial and biennial middle dry season fires, both performed in August but at different frequencies, behaved similarly. The parameters of fire that charac-

Table 4 Soil properties for the different fire regimes during the wet and dry seasons in 2008 (means and standard deviations [sd] for each season). Means followed by the same small case letter do not differ significantly between the two sampling seasons ($p<0.001$)

Soil variable	Sampling season	Unburned		Biennial early dry season		Biennial middle dry season		Biennial late dry season		Quadrennial	
		Mean	sd	Mean	sd	Mean	sd	Mean	sd	Mean	sd
Soil pH ($CaCl_2$)	Wet	4.17a	0.07	4.27	0.05	4.26a	0.07	4.34a	0.17	4.37a	0.08
	Dry	4.17a	0.04			4.11a	0.05	4.23a	0.09	4.21	0.10
Organic matter (g kg^{-1})	Wet	55.70a	8.05	54.52	5.89	49.17a	5.74	52.41a	10.57	54.05a	8.58
	Dry	39.22a	5.35			35.71a	5.40	36.03a	5.59	31.95a	5.80
Potential acidity (mmol· kg^{-1})	Wet	90.04a	14.32	78.76	7.67	77.16a	9.93	71.06a	14.70	69.96a	10.84
	Dry	89.69a	8.07			90.55b	9.01	81.94a	10.83	79.37a	15.64
P (mg kg^{-1})	Wet	3.69a	1.50	3.33	1.44	4.06a	1.48	2.35a	1.84	2.44a	1.73
	Dry	1.78b	1.70			2.20b	0.92	1.50a	0.88	1.84a	1.00
N (g kg^{-1})	Wet	2.11a	0.28	2.01	0.14	1.93a	0.21	1.91a	0.32	1.88a	0.17
	Dry	1.83b	0.11			1.63b	0.13	1.60b	0.17	1.58b	0.19
K (mmol kg^{-1})	Wet	1.82a	0.49	1.86	0.37	1.99a	0.62	2.67a	1.47	2.35a	0.55
	Dry	2.13a	2.05			2.34a	2.03	1.36b	0.32	1.23b	0.38
Ca (mmol kg^{-1})	Wet	2.44a	1.42	2.74	1.59	2.79a	1.44	2.70a	2.05	2.79a	1.56
	Dry	0.56a	0.43			0.47a	0.27	1.41a	1.08	0.80b	0.64
Mg (mmol kg^{-1})	Wet	1.96a	1.19	2.31	1.03	1.97a	0.56	2.36a	1.41	2.67a	1.21
	Dry	1.08a	0.21			1.03a	0.25	1.51a	0.61	1.18b	0.46
Sum of bases (mmol kg^{-1})	Wet	6.22	2.68	6.91	2.72	6.76	1.80	7.72	4.16	7.80	2.90
	Dry	3.78	2.16			3.84	2.03	4.28	1.65	3.22	1.18
S (mg kg^{-1})	Wet	3.92a	0.71	1.15	0.80	3.32a	0.69	3.21a	1.05	1.98a	1.19
	Dry	1.48b	0.84			1.70b	0.80	1.68b	0.71	1.63a	0.67
Cu (mg kg^{-1})	Wet	1.11a	0.33	1.08	0.3	0.81a	0.57	0.76a	0.19	0.60a	0.24
	Dry	0.66b	0.10			0.52a	0.13	0.62b	0.13	0.40b	0.07
Fe (mg kg^{-1})	Wet	104.1a	35.46	87.16	16.11	70.16a	16.91	84.45a	33.36	81.41a	21.71
	Dry	78.43b	16.56			68.73a	19.67	72.97a	17.64	68.71a	21.73
Mn (mg kg^{-1})	Wet	4.14a	1.84	3.38	1.36	2.30a	0.74	3.73a	1.50	4.64a	1.67
	Dry	1.56b	0.45			0.97b	0.47	1.61b	0.56	1.25b	0.48
Zn (mg kg^{-1})	Wet	0.47a	0.22	0.29	0.07	0.24a	0.11	0.33a	0.17	0.25a	0.09
	Dry	0.14b	0.04			0.11b	0.03	0.21a	0.38	0.11b	0.02
Cation exchange capacity (mmol kg^{-1})	Wet	96.26	15.75	85.67	9.05	83.92	10.27	78.78	15.90	77.76	11.55
	Dry	93.47	8.64			94.39	8.78	86.22	10.66	82.58	15.82

terize its behavior, such as the heat released, fire intensity and spread, are determined mostly by fuel and climate conditions at the moment of fire provided there is enough fuel to conduct a fire.

Maximum air temperatures occurred at 60 cm, just above the herbaceous layer, but high temperatures above 700°C also occurred at 1 cm above the soil surface. The duration of temperatures above 60°C, even though long enough to damage the vegetation, was not sufficient to heat the soil considerably. Maximum soil temperatures of around 31°C at 1 cm depth observed in this study were in the lower range of soil temperatures measured during open cerrado fires (29°C to 55°C) reported by Coutinho (1990) and Miranda et al. (1993).

Although cerrado fires are of low intensity and soil temperatures do not reach high values, our results provide evidence of long-term fire effects in soil

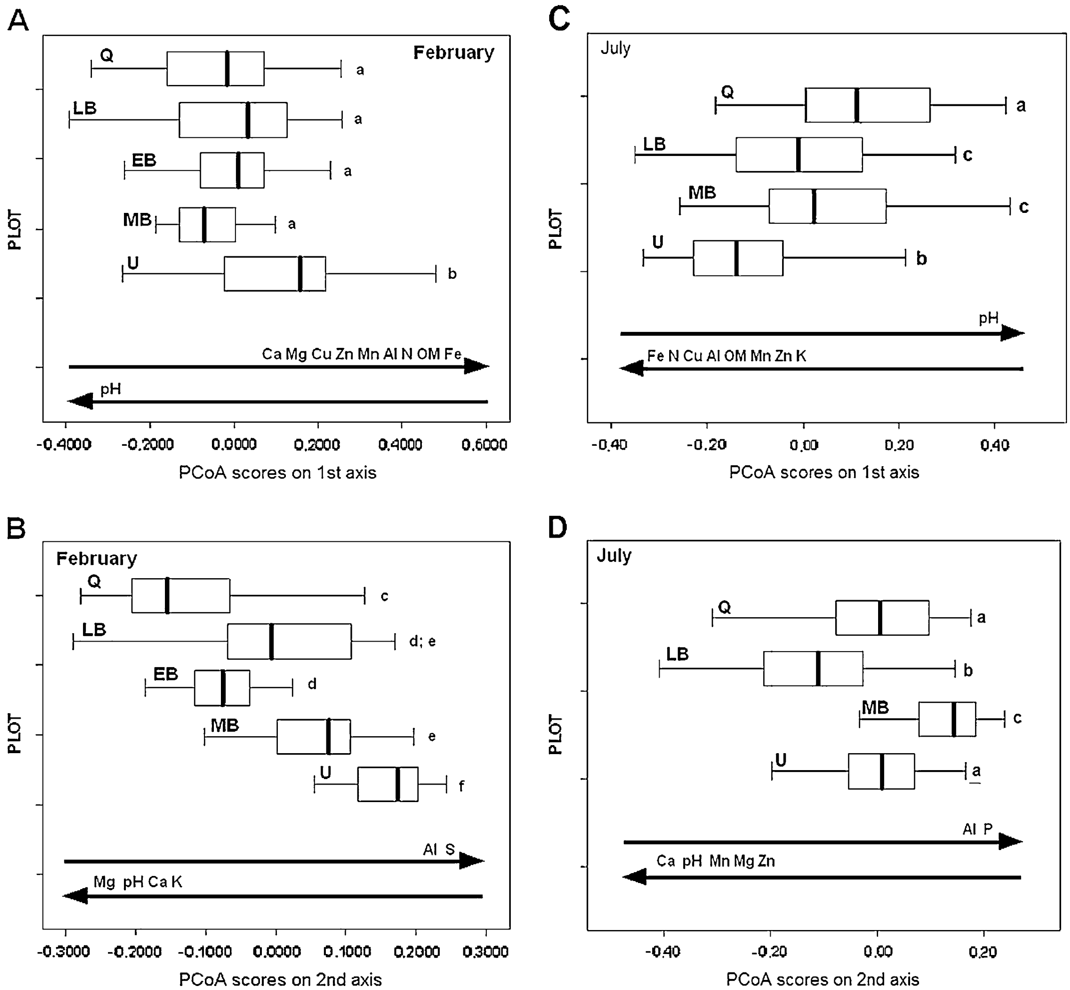

Fig. 3 Scores resulting from the principal coordinates analysis (PCoA) applied to soil samples from the wet (February, **a** and **b**) and dry (July, **c** and **d**) seasons of 2008. *Boxes* show median (*vertical line*), 95% confidence interval (*box*) and standard error (*lines*). Fire regimes with the same *lowercase letter* show no significant differences in mean score. *Arrows* indicate significant correlation of soil variables with the gradient in order of strength (outer is stronger). Only variables with correlation >0.40 are shown. *Uppercase letters* identify fire regimes: *U* control; *Q* quadrennial fires; *EB* biennial early dry season fires; *MB* biennial middle dry season fires; *LB* biennial late dry season fires

acidity and nutrient availability. The high acidity and low values of soil nutrients reported here were comparable with data for other cerrado soils which occur typically in very old and leached terrains associated with laterite deposits (Adálmoli et al. 1987; Haridasan 1994; Reatto et al. 2008). The analyses of soil variables from both wet and dry seasons showed that the unburned plot was segregated from the other treatments. The quadrennial fire plot was the most dissimilar amongst the fire plots but similar to the unburned plot. The biennial treatment plots showed to be similar among themselves, independent of the timing of fires during the dry season. It seems probable that a gradient following fire frequencies has been established as far as the soil variables investigated in the present study are concerned. Seasonal effects of each biennial fire, however, were not evidenced by our data.

Spearman correlation analyses indicated soil pH to be the main factor responsible for segregating the fire treatments into different groups with a consistent pattern. Soil pH was higher in the burned than in the unburned plots, probably because of the alkaline effect of the ash deposited at the soil surface after fires. The effect of ash deposition explains also the higher availability of Ca, Mg and K in the burned plots, as

Table 5 Spearman correlation coefficients between the axes scores and the soil variables for the wet and dry season samplings

Soil variable	Axis 1	Axis 2
Wet season		
Soil pH ($CaCl_2$)	−0.406 **	−0.580 **
Organic matter (g kg^{-1})	0.793 **	NS
Potential acidity (mmol kg^{-1})	0.667 **	0.434 **
P (mg kg^{-1})	NS	NS
N (g kg^{-1})	0.757 **	NS
K (mmol kg^{-1})	0.381 **	−0.405 **
Ca (mmol kg^{-1})	0.402 **	−0.535 **
Mg (mmol kg^{-1})	0.429 **	−0.662 **
S (mg kg^{-1})	NS	0.711**
Cu (mg kg^{-1})	0.498 **	NS
Fe (mg kg^{-1})	0.862 **	NS
Mn (mg kg^{-1})	0.664 **	−0.336 **
Zn (mg kg^{-1})	0.649 **	0.267 **
Dry season		
Soil pH ($CaCl_2$)	0.417 **	−0.698 **
Organic matter (g kg^{-1})	−0.682 **	NS
Potential acidity (mmol kg^{-1})	−0.695 **	0.402 **
P (mg kg^{-1})	NS	0.537 **
N (g kg^{-1})	−0.803 **	NS
K (mmol kg^{-1})	−0.465 **	NS
Ca (mmol kg^{-1})	NS	−0.734 **
Mg (mmol kg^{-1})	−0.388 **	−0.551 **
S (mg kg^{-1})	NS	−0.228**
Cu (mg kg^{-1})	−0.720 **	−0.220 **
Fe (mg kg^{-1})	−0.817 **	NS
Mn (mg kg^{-1})	−0.635 **	−0.609 **
Zn (mg kg^{-1})	−0.622 **	−0.444 **

**=$p \leq 0.01$, 2-tailed test; *NS* not significant

the ash releases basic cations which temporarily increase soil pH, reduce exchangeable Al, available Fe and Mn, and promote fertilization due to soluble compounds added to soil (Rundel and Parsons 1984; Coutinho 1990; Sollins 1998; Neary et al. 2005). These effects could be important in Brazilian cerrados, where soils often have high levels of available Al, Fe and Mn (Malavolta et al. 1977; Haridasan 1982; Queiroz-Neto 1982; Adámoli et al. 1987; Coutinho 1990). The amounts of available Cu and Zn at the experimental site were very low which might reflect the high degree of soil weathering and leaching (Cakmak 2008). Higher levels of Zn and Cu in the unburned plot might be due to lower pH values, as acidity increases the availability of these elements. The same happens with Fe, Al and Mn (Malavolta et al. 1977; Kparmwang et al. 1998; Cakmak 2008). Both in the wet and dry seasons, pH showed negative correlations with potential acidity, Cu, Fe, Zn, Mn and organic matter and positive correlations with K, Ca, Mg.

The few studies that registered long-term (residual) effects of fire on Brazilian soils have shown different results. In another area of cerrado on a Latosol, Silva and Batalha (2008) obtained results similar to ours with higher values of pH, N, K and Mg and lower levels of Al in annually burned sites as compared to less frequently burned sites. Rheinheimer et al. (2003) also reported increase in bases and decrease in Al levels in a Cambisol under native pasture immediately after fire, however, these effects persisted only 90 days. Dick et al. (2008) found opposite tendencies of lower levels of Mg, K and Ca and higher levels of Al in a Cambisol pasture 8 years after burning as compared to unburned sites. Thus, similar conditions of soil characteristics and vegetation cover seem to result in comparable changes in nutrient dynamics in the surface soil.

There was a tendency towards lower levels of N and S in burned plots, particularly in the wet season. In addition to the ash generated when the vegetation

Table 6 Comparisons between wet (February) and dry season (July) soil parameters

Soil variable	MB	LB	Q	U
pH ($CaCl_2$)	**	NS	**	NS
Organic matter (g kg^{-1})	**	**	**	**
Potential acidity (mmol kg^{-1})	**	NS	NS	NS
P (mg kg^{-1})	**	NS	NS	**
N (mg kg^{-1})	**	**	**	**
K (mmol kg^{-1})	NS	**	**	NS
Ca (mmol kg^{-1})	**	NS	**	**
Mg (mmol kg^{-1})	**	NS	**	**
S (mg kg^{-1})	**	**	NS	**
Cu (mg kg^{-1})	NS	**	**	**
Fe (mg kg^{-1})	NS	NS	NS	**
Mn (mg kg^{-1})	**	**	**	**
Zn (mg kg^{-1})	**	NS	**	**

Two-tailed *t*-test; **=$p \leq 0.01$; *NS* not significant is burned, part of the elements contained in plant and litter tissues go to the atmosphere, either as particles or as volatile substances. Pivello and Coutinho (1992) and Kauffman et al. (1994) demonstrated that more than 90% of N and about 60% of S are easily lost to the atmosphere during fires, besides the loss of carbon from the organic matter. The extent of these losses depends on the temperatures reached during the fires, which govern volatilization. N and S are highly volatile elements, requiring relatively low temperatures (200–300°C) to volatilize (Boerner 1982). However, except for the soil surface, temperatures in the soil were not high enough to volatilize even these elements. But as they are lost from the vegetation to a great extent, ashes are poor in N and S, and do not carry these elements to the soil. Dick et al. (2008) and Rheinheimer et al. (2003) also obtained lower values of N in burned Cambisol pastures compared to the unburned areas, some months or years after fire.

The comparison of soil chemical parameters between wet and dry season revealed higher availability of macro and micronutrients in the wet season samples. Large amounts of elements, especially S and Ca, besides P and K, were quantified in a cerrado rainfall (Coutinho 1979) and, as February is one of the rainiest months in the cerrado region, a significant amount of these elements could be expected to come via rainfall. The rainy season in the cerrado region is also the warmest time of year, when higher microbial activity would be expected. Elements such as N, P and S, whose dynamics are strongly related to microbial activity in the soil, may also be mineralized at higher rates during the wet season, when microbial activity is more intense (Christensen 1973; Raison 1979; Bustamante et al. 2006). Singh and Kashyap (2007) concluded that variations in rates of N-mineralization and nitrification in dry tropical ecosystems were related to differences in soil moisture content, nutrient status and vegetation cover in combination with other environmental factors. The cerrado region supports a mosaic of plant physiognomies and heterogeneous plant communities on nutrient deficient soils. Although topography and climatic factors are important in determining the distribution and productivity of ecosystems, alterations of nutrient cycling due to frequent fires could be important in determining changes in these ecosystems.

Conclusion

Our results show that, in *campo sujo*, fire characteristics that determine fire behavior (such as fireline intensity, rate of fire spread, heat released per area, and air temperatures) vary with the time of burning during the dry season, as climatic conditions determine most variables involved in fire behavior. On the other hand, the availability of nutrients in the soil is not affected by the time of burning, but by fire frequency. These results are relevant for establishment of prescribed fires for management of cerrado vegetation. The safety of a prescribed fire is greatly related to the burning season. Early winter fires, when there is more humidity in the soil and in the environment, tend to be milder. Still, our results showed that the alkalinization and fertilization effects promoted by the ash in periodically burned open cerrados can persist for at least 2 years.

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