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Transfer of macro-nutrients to the atmosphere during experimental burnings in an open cerrado (Brazilian savanna)

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ABSTRACT. This paper presents the quantities of macro-nutrients (N, P, K, Ca, Mg and S) released from the ground layer vegetation to the atmosphere during six experimental burnings, in a Brazilian open savanna, named 'campo-cerrado'. The values were obtained by comparing the amounts of nutrients in the fuel and in the ash resulting after the burn, in three different seasons. On average, 20.6 kg of N, 1.6 kg of P, 7.1 kg of K, 12.1 kg of Ca, 3.0 kg of Mg, and 3.2 kg of S ha^{-1} were transferred from the plant biomass to the atmosphere, representing mean percentages of 95% for N, 51% for P, 44% for K, 52% for Ca, 42% for Mg, and 59% for S. The burn season showed no significant influence on the amounts of nutrients transferred to the atmosphere. Some relationships involving the quantities of macro-nutrients released, fuel moisture, the combustion efficiency during the burns, and the initial standing biomass in the area were also tested. Comparing the average output of macro-nutrients to the atmosphere obtained in this study with their inputs via rainfall, in the same area, it was estimated that three years would be an adequate interval between prescribed burnings for this campo-cerrado, to speed up nutrient recycling without impoverishing the system.

RESUMO. Neste estudo, foram quantificadas as transferências de macro-nutrientes (N, P, K, Ca, Mg, S) da vegetação herbáceo-subarbustiva para a atmosfera durante seis queimadas experimentais realizadas no campo-cerrado de Emas, em Pirassununga, S.P., em três diferentes épocas do ano. Estes valores foram obtidos comparando-se as quantidades dos nutrientes na vegetação e na cinza dela resultante, após a queima, Em média, 20.6 kg de N, 1.6 kg de P, 7.1 kg de K, 12.1 kg de Ca, 3.0 kg de Mg e 3.2 kg de S foram liberados para a atmosfera, o que representa 95% do N, 51% do P, 44% do K, 52% do Ca, 42% do Mg e 59% do S inicialmente contidos na fitomassa. A época em que a queimada foi realizada não teve influência significativa no processo. Foram testadas algumas correlações envolvendo as transferências dos nutrientes, a biomassa fresca do material combustível, seu teor de umidade e a eficiência de combustão durante as queimadas, encontrando-se algumas correlaçoes significativas a 95% de confiança. Comparando-se as quantidades dos macro-nutrientes liberados durante a queima da vegetação com sua volta ao solo através da água de chuva (exceto N), foi estimado que um intervalo de três anos entre queimadas sucessivas é necessário e adequado para promover sua ciclagem no ecossistema estudado, sem afetar negativamente seu balanço nutricional.

KEY WORDS: Brazil, cerrado, burning, fire, macro-nutrients, nutrient cycling, savanna.

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INTRODUCTION

The Brazilian open cerrados (a type of savanna) are exposed to accidental or intentional burnings periodically; natural fires, due to lightning, are less frequent but also occur. As in most savanna ecosystems, fire is not a new feature of the cerrados – pieces of charcoal found in the soil of Emas Cerrado (São Paulo, Brazil) were estimated as 8600 years old (Coutinho 1981).

Cerrados are usually burned either for deforestation, with subsequent change to agricultural use, or to stimulate the regrowth of fresh and more palatable forage for cattle during the dry season, in the areas used as natural pastures (Coutinho 1980, Eiten 1972).

Many of the effects of fire on the physical and chemical properties of the soil, on microclimate, and on flora and fauna in several different types of savannas were described by Booysen & Tainton (1984), Coutinho (1982), Daubenmire (1974), Gill *et al.* (1981). Nutrient cycles are also markedly affected, since large amounts of nutrients are either deposited over the soil as ash or transferred to the atmosphere through smoke and volatile compounds (Boerner 1982, Pivello 1985). Fire also speeds up nutrient cycling, making available to plants those elements retained in dead material (Seastedt 1985, Wright & Bailey 1982).

The main objective of the work reported here was to quantify the macronutrients (N, P, K, Ca, Mg and S) released from the ground layer vegetation to the atmosphere after burning an open cerrado ecosystem, in São Paulo State, Brazil. These nutrient losses to the atmosphere were also compared with rainfall input, and their average replacement times by rainwater were estimated. This allows a preliminary assessment of the minimum interval between prescribed burnings necessary to minimize disturbance to the nutrient balance in that ecosystem.

THE STUDY AREA

The study site is part of the Emas Cerrado, at Pirassununga town, São Paulo State, Brazil. It is situated in a gently rolling terrain, at an average altitude of 600 m. The climate is warm and humid during most of the year, but with a dry period in the winter, which usually lasts from April to September, interrupted by one or two more humid months (Cwa climate, following Koeppen's (1948) classification). Mean temperatures for the warmest months are around 23–24°C and fall to 15–16°C for the coldest months. The average rainfall per year is around 1300 mm and mostly concentrated between October and March (Reis 1971). These features, except for the last year (1983), which was unusually wet, can be observed in the climate diagrams produced for the years of study (Figure 1, following Walter *et al.* 1975). The soil type is oxisol (ferralitic soil, classified as a red-yellow latosol, in the Brazilian terminology), typically deep, acid, leached, well drained, and nutrient-poor (described in detail by Oliveira *et al.* 1982).

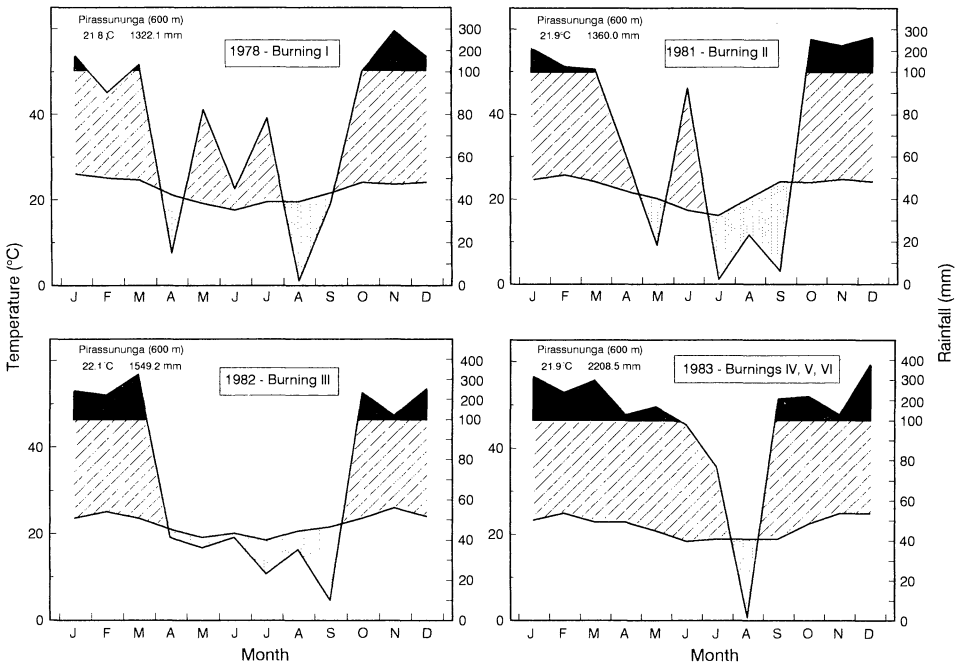

Figure 1. Climate diagrams for the years when experimental burnings occurred, following the method of Walter *et al.* (1975).

The area is an open woodland savanna, with a continuous ground layer mainly formed by tall and coarse grasses, Compositae, sedges, and leguminous sub-shrubs; trees are scattered and short (4–6 m). This type of vegetation was classified as 'campo-cerrado' by Coutinho (1978) and Goodland (1971), or as 'wooded savanna', by Sarmiento (1983). The first terminology is used here, since it is more specific for this vegetation (see Eiten 1979).

The cerrados in this region experience periodic man-made fires every two years, but occasionally more frequently.

METHODS

The amounts of macro nutrients released from the ground layer to the atmosphere were quantified by determining the difference between the amounts in the vegetation before burning, and in the resultant ash.

Six experimental burnings were conducted in the following dates: I – 17 July, 1978; II – 07 September, 1981; III – 15 May, 1982; IV – 13 and 22 June, 1983; V – 26 July, 1983; and VI – 02 October, 1983. The plots, one for each burning, were polygons of about 1 ha, protected by 2 m wide firebreaks, and which had not been burned for 1–2 years before the experimental burnings.

In each plot, ten 1.0 m^2 samples of the ground layer standing crop were collected randomly by clipping to ground level, and biomass, water content, macro-nutrient content, and weight loss on ignition (LI) were determined. To

collect samples of ash, 100 fire-proof glass dishes (area = 78.5 cm^2) were distributed along a transect within the plot. As only the ground layer was considered in this study, the dishes were not put near or below trees or shrubs, in order to avoid collecting the ash coming from this stratum. The 100 samples were then combined into 10 compound samples.

Burnings were made in the hottest and driest period of the day (1300–1400 h). A headfire (following the wind direction) was lit in the upwind border of the plot, enabling it to spread through the whole of the plot. In burning IV, fire did not spread uniformly at the first attempt, so the burn was repeated 9 days later and the ash collected on both occasions was pooled.

The fuel and ash samples collected were oven dried at 60°C to a constant weight before being analysed. Fuel and ash LI's were determined by igniting the dried material at 550°C for 3 h. Combustion efficiency (CE) in the experimental burnings was determined as:

$$CE = 100\ (1 - [\text{ash LI}/\text{fuel LI}]).$$

Macro-nutrient concentrations in fuel and ash were then determined, according to the methodology used in the Centro de Energia Nuclear na Agricultura (CENA – Piracicaba, São Paulo State), described in detail by Zagatto *et al.* (1981). Samples of ash and fuel were digested with $HClO_4$, HNO_3 and H_2SO_4. Total N was quantified by the blue indophenol reaction method, using a Technicon Auto Analyser; K by atomic absorption spectrophotometry in air-acetylene flame, using a Perkin-Elmer AAS 306; P, Ca, and Mg by atomic emission spectrometry with plasma induced in argon, using a computerised spectrometer system (Jarrell-Ash Plasma Atomcomp Direct Reading Spectrometer); S (as barium sulphate) was quantified by turbidimetry, using a flow injection system.

Seasonal effects on fuel moisture and on the quantities of each nutrient released to the atmosphere were tested by single factor analyses of variance (ANOVA). Relationships between the macro-nutrient releases and fuel moisture, CE, standing biomass, and rainfall 30 days before each burning were tested by simple linear correlation analysis (Zar 1984).

The average replacement times for P, K, Ca, Mg and S via rainfall were estimated using Coutinho's (1979) data on rainfall inputs for the same area.

RESULTS

Fuel fresh weight in the plots varied between 6.5 and 11.6 $t\,ha^{-1}$, dry weights between 4.9 and 7.7 $t\,ha^{-1}$ and moisture between 21 and 44%. LI values were high, around 90% of the dry weight (Table 1). Ash LI values of 22% to 33% indicate that combustion was incomplete in all six burnings, with CE figures showing greatest efficiency in burn II (77%) and the lowest in burn V (63%) (Table 1).

Table 1 Fresh and dry fuel biomass, fuel moisture, ash dry weight, fuel and ash weight losses on ignition (LI) and combustion efficiency (CE) values for six experimental burnings in a Brazilian campo-cerrado (Mean ± confidence interval at P = 0.05); * = value not determined

	Fuel				Ash		CE
Burning	Fresh weight ($t\,ha^{-1}$)	Dry weight ($t\,ha^{-1}$)	Water content (%)	LI (%)	Dry weight ($t\,ha^{-1}$)	LI (%)	(%)
I	*	7.7 ± 0.7	*	92	0.36 ± 0.05	28	70
II	6.5 ± 1.0	5.1 ± 0.9	21	94	0.33 + 0.04	22	77
III	7.4 ± 1.2	4.9 ± 1.0	35	94	0.26 ± 0.04	23	76
IV	11.6 ± 1.2	6.5 ± 0.7	44	91	0.32 ± 0.04	32	65
V	11.4 ± 1.4	7.0 ± 0.8	39	88	0.40 ± 0.05	33	63
VI	11.2 ± 1.3	7.5 ± 0.8	33	90	0.45 ± 0.04	28	69

The average amounts of nutrients transferred to the atmosphere during the six experimental burnings were, in $kg\,ha^{-1}$: N, 20.6; P, 1.6; K, 7.1; Ca, 12.1; Mg, 3.0; S, 3.2 (Figure 2). When expressed as a percentage of total fuel content, very high losses occur, especially for N (always more than 90% released to the atmosphere) (Table 2). It is also noticeable that the highest losses of P, K, Ca and Mg occurred during burning IV, when the plot was submitted to a double burn.

The ANOVA showed no significant influence of burning date (events I–VI) on the release to the atmosphere of the six nutrients analysed at P = 0.05. Similarly, seasonal effect on fuel moisture was not significant. However, it must be noticed that 1983 (when burnings IV, V and VI took place) was an exceptionally wet year (Figure 1) and the typical seasonal pattern did not happen.

Transfers of Ca and Mg to the atmosphere were correlated significantly (P = 0.05) with fuel moisture and CE – positively in the former situation and negatively in the latter (Table 3). However, relationships between the element losses and rainfall in the last 30 days before the burn were not significant. CE shows a significant and negative correlation with the standing biomass but no significant correlation with fuel moisture and rainfall. Positive and significant associations also occurred between Ca transfers and the standing biomass.

A preliminary estimate of the macro-nutrient replacement via rainfall is presented in Table 4. It shows a very rapid return of the elements, especially P and S.

DISCUSSION

The initial idea was to quantify and to compare the quantities of macro-nutrients released to the atmosphere in early (before July), mid (July/August) and late (after August) burns, according to rainfall seasonality, but the unusual rainfall regime in 1983 changed the expected seasonal pattern and increased fuel moisture

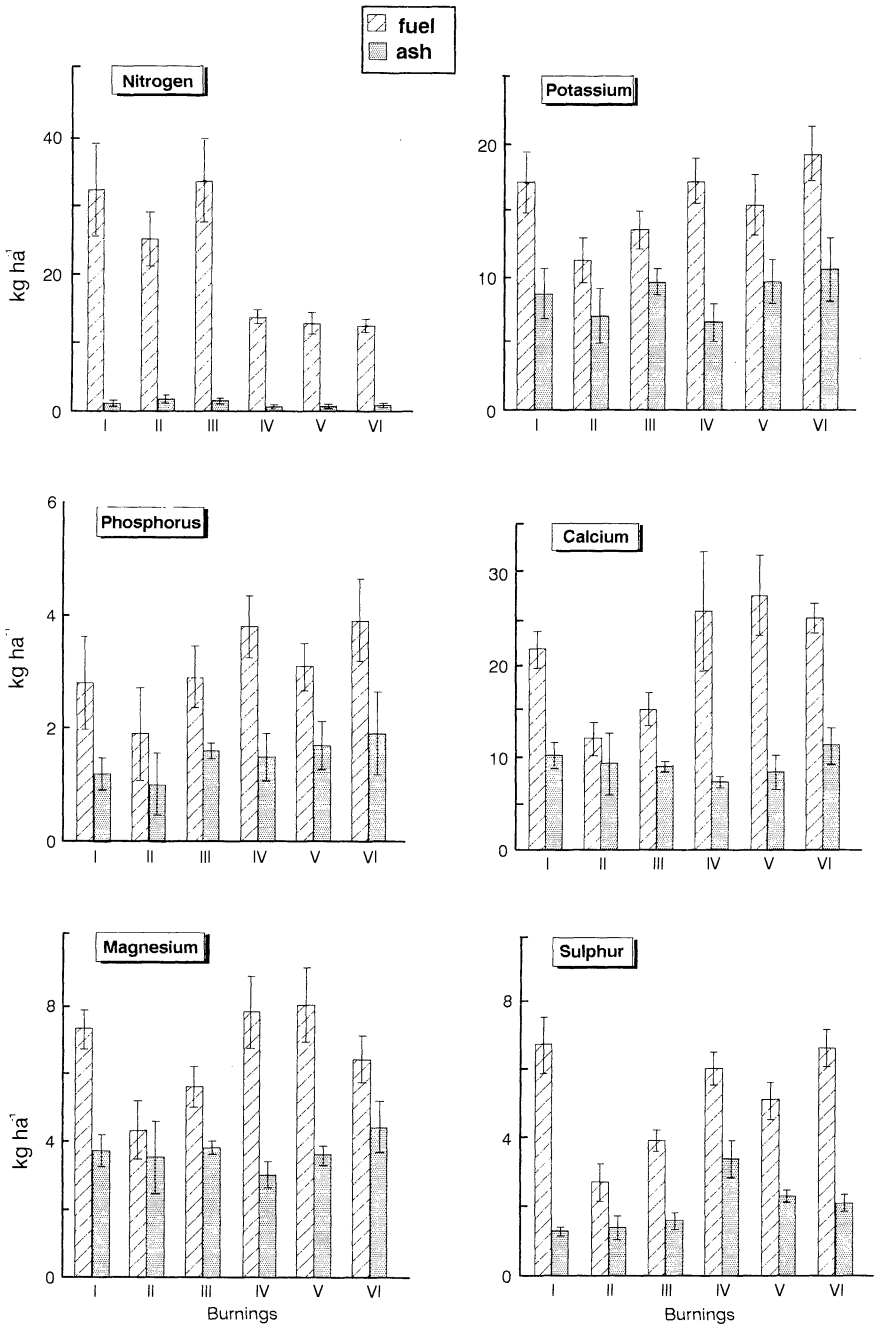

Figure 2. Macro-nutrient contents in fuel (before fire) and in ash (after fire), in kg ha^{-1} (Mean ± Standard error; N = 10).

Table 2. Quantities of macro-nutrients released to the atmosphere during the experimental burnings, expressed as percentage of the total fuel content.

Burning	N	P	K	Ca	Mg	S
I	97	57	49	53	49	81
II	93	47	38	22	19	48
III	96	45	29	40	32	59
IV	96	61	62	71	62	43
V	95	45	38	69	56	55
VI	94	51	45	55	31	68

Table 3. Correlation coefficients for the relationships involved, at P = 0.05; df = 4; * df = 3 (tr = percentage of the nutrient transferred to the atmosphere; CE = combustion efficiency; NS = non-significant).

	N tr	P tr	K tr	Ca tr	Mg tr	S tr	Fuel water content*	Standing biomass	Rainfall
CE	NS	NS	NS	−0.95	−0.86	NS	NS	−0.95	NS
N tr	–	NS	NS	NS	NS	NS	NS	NS	NS
P tr	–	–	+0.95	NS	NS	NS	NS	NS	NS
K tr	–	–	–	NS	NS	NS	NS	NS	NS
Ca tr	–	–	–	–	NS	NS	+0.92	+0.95	NS
Mg tr	–	–	–	–	–	NS	+0.92	NS	NS
S tr	–	–	–	–	–	–	NS	NS	NS

Table 4. Nutrient inputs via rainfall, outputs to the atmosphere during burnings and estimated turnover times, in Emas Cerrado (São Paulo, Brazil).

	N	P	K	Ca	Mg	S	Author
Input ($kg\,ha^{-1}\,y^{-1}$)	–	2.89	2.57	5.60	0.90	35.86	Coutinho 1979
Output ($kg\,ha^{-1}$)	11.6–32.0	0.9–2.3	4.0–10.6	2.7–19.1	0.8–4.8	1.3–5.4	This research
Turnover time (y)	–	< 1.0	1.6–4.1	< 1.0–3.4	< 1.0–5.3	< 1.0	This research

content. The burnings could not be classified as such and are therefore considered independently.

According to Burgan & Rothermel (1984), fuel moisture affects ignition and fire spread rate, and this explains the difficulty in getting a uniform fire in burn IV. Higher percentages of nutrients lost in this burning were probably because of the double burn in this plot. On the other hand, fuel moisture does not seem to affect CE (no significant correlation was found). Moreover, it appears not to influence the temperatures reached during the burn, according to Stronach & McNaughton (1989), who say: 'variation in heat yield is... little affected by plant moisture content, provided the material is dry enough to burn'. These

Table 5. Macro-nutrient transfers (%) from vegetation to the atmosphere after burns under field conditions.

Ecosystem	Nutrient losses						Author
	N	P	K	Ca	Mg	S	
Native pasture/ Australia	90–96	–	–	–	–	–	Norman & Wetselaar 1960
Coniferous forest/ USA	97	–	79	20	31	–	Grier 1975
Pine-wiregrass savanna/USA	70	46	40	16	14	–	Christensen 1977
Chaparral/USA	75	92	79	63	77	–	DeBano & Conrad 1978
Savanna/Ivory Coast	90	23	46	5	–	–	Villecourt & Roose 1978
Coniferous forest/ USA	14	–	–	–	–	17.5	Richter *et al.* 1982
Eucalypt forest/ Australia	54–75	37–50	43–66	31–34	25–49	–	Raison *et al.* 1985
Campo-cerrado/Brazil	93–97	45–61	29–62	22–71	19–62	43–81	This research

authors attribute the heat produced in a fire mainly to 'plant mass density' (fuel biomass). They found that CE too was associated with the initial standing biomass and this study confirms this, as the CE was lower when more fuel was available to burn. Stronach & McNaughton suggested that 'air supply may limit combustion in fires consuming more than about 800 g m^{-2} (8000 kg ha^{-1})', which may have happened in burnings IV, V and VI. The values here obtained for CE (63–77%) are comparable to Stronach's & McNaughton's figures for Serengeti National Park savannas: 49–84%.

Higher figures were obtained for Ca and Mg loss to the atmosphere after burning, which contrast with the low values (between 0 and 15%) reported by Allen (1964), Evans & Allen (1971), and Lloyd (1971), who incinerated plant material (from temperate ecosystems) in a furnace, at temperatures up to 900°C. However, these figures are in the same range as those obtained for other burns under field conditions (Table 5). Wind may be a key factor to explain the much higher values obtained for burnings in the field, as it plays an important role in the transport of ash.

As very high temperatures (> 1100°C) are required to volatilize both Ca and Mg (Wright & Bailey 1982) and such temperatures are not reached in cerrado fires (Miranda *et al.* 1989), most losses of these elements were probably through flying ash. Other evidence meets this assumption: the moister the fuel, the more smoke is produced when it is burned, which carries particles away. Accordingly, a significant positive correlation was found between Ca and Mg losses and the fuel moisture. Also, their losses correlated significantly and negatively with CE and, as say Raison *et al.* (1985), 'particulate contributions to elemental transfers are less where combustion is more complete'.

In contrast to Ca and Mg, very large N losses to the atmosphere were apparently independent of CE or fuel moisture. High N losses have been also

reported by other authors, either when burning plant material in laboratory or in the field. Allen's (1964) and Evans' & Allen's (1971) experiments, under laboratory conditions, showed that all the nitrogen was lost at both 400°C and 500°C. For field experiments, values ranged from 54–97% (see Table 5). Nitrogen has a relatively low volatilization temperature, about 200°C to 300°C (Boerner 1982) which may explain the great losses reported by other authors and in the present work.

According to Boerner (1982) and Vlamis & Gowans (1961), sulphur is also a highly volatile element and high S transfers (43–81%) were also registered, although not as high as for N, and much more variable. Very few authors have quantified S losses during burnings in the field and the value presented by Richter *et al.* (1982), for a pine forest, is much lower than the ones obtained in this study (Table 5). Like N, S releases do not appear to be linked to fuel moisture or CE.

Transfer of K and P during burnings might be controlled by similar factors, as they show positively correlated behaviour to each other. The data obtained here are relatively similar to those found in two other savannas (Christensen 1977 and Villecourt & Roose 1978) and in an eucalyptus forest (Raison *et al.* 1985), as both chaparral and coniferous forest lost greater amounts of P and K (Table 5). According to Raison *et al.* (1985), the transport of P and K to the atmosphere occurs either in particulate or non-particulate forms.

Despite the large amounts of macro-nutrients released to the atmosphere during burnings in Emas campos-cerrados, their return by rainfall or gravity seems to be very rapid. Using Coutinho's (1979) data of nutrient inputs via rainfall for the same area and comparing them with the data obtained here (Table 4), it was preliminarily estimated that the replacement time of P and S was far less than 1 y; for Ca, < 1–3.4 y; for K, 1.6–4.1 y; and for Mg, < 1–5.3 y. Compared with Schiavini's (1984) data on nutrient inputs via rainfall for another cerrado region, the estimated replacement times for K and Mg show very similar values. Although neither Coutinho (1979) nor Schiavini (1984) quantified N inputs by rainfall, its return must be rapid also, because of the activity of N fixing bacteria, which are common in cerrado soils (Suhet *et al.* 1987), and to N inputs in rain water.

However, even this apparent rapid return of macro-nutrients cannot compensate for the losses of some of them, especially K, caused by the present fire regime, where burns became more frequent (every 2 y or less) with the increase in population density and the consequent pressure on the environment. As a result, the already poor cerrado soils are becoming even poorer and tree density is decreasing.

Although additional series of element inputs and outputs are necessary for a more conclusive estimation, a 3 y interval between burnings is initially considered adequate to stimulate the recycling of the elements retained in dead plant material and to avoid a critical nutrient impoverishment in that ecosystem, taking into account the average quantities of macro-nutrients released to the

atmosphere due to fire and their replacement through rainwater, and bearing in mind the rapid build up of dead organic matter in open cerrados. Also, burning when the fuel is drier, with water content around 20%, may help to reduce Ca and Mg losses.

CONCLUSIONS

The main conclusions drawn from this research can be summarized as follows:

1. The combustion of the ground layer plant biomass during the experimental burnings was incomplete, around 70%.
2. CE was inversely associated with standing crop biomass.
3. The nutrient dynamic in cerrado ecosystems is highly influenced by fire; almost all N present in plant fuel and large amounts of the other macro-nutrients were released to the atmosphere, either as volatile compounds or as flying ash.
4. Ca and Mg transfers to the atmosphere were positively correlated with fuel moisture and negatively with CE. Ca releases were also correlated with fuel biomass.
5. Burning when fuel is dry reduces Ca and Mg losses to the atmosphere.
6. The macro-nutrients released to the atmosphere due to fire can quickly return to the soil. Their replacement times (excluding N) were preliminarily estimated at less than 1 y to, at most, 5.3 y.
7. In the ecosystem considered, a 3 y interval between successive burns seems to be adequate to promote nutrient recycling without impoverishing the macronutrient pool.

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