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Pedology and plant physiognomies in the cerrado, Brazil

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ABSTRACT

This study was carried out in Paraopeba National Reserve. It aims to classify and evaluate the soil of the studied area and to verify the influence of soil attributes on vegetation by testing the following hypotheses: 1) under woodland physiognomies (Cerradão) the soil fertility is higher and the Al content lower; 2) open savanna occurs only in areas with high Al contents. For this purpose, representative soils in the Paraopeba National Reserve were mapped, identified, and samples from five profiles were analyzed. The environmental gradient was easily observed by principal components analyses, where the differences between the sites were highlighted. The Spearman correlation was used to verify the hypothesis. The correlation between vegetation (basal area, density, and richness) and soil (K, Ca^{2+}, and Al^{3+}) was statistically significant. The hypotheses were accepted, but hypothesis 1 only partially. Soil features seem to have an influence on the Cerrado phytophysiognomies and structure. Available phosphorous was an important factor for the maintenance of woodland Cerrado. Also, exchangeable Al^{3+} plays a major role in the establishment of different Cerrado physiognomies in Paraopeba National Reserve.

Key words: aluminum tolerance, brazilian savanna, edaphic features, soil fertility, soil-vegetation gradient.

INTRODUCTION

The Cerrado vegetation is the major neotropical savanna and stretches over one and a half million square kilometers in tropical South America. Cerrado is limited in the north-northwest by the Amazon Forest, in the south and southeast by the Brazilian Atlantic Forest, in the Northeast by the Semi-Arid Caatinga vegetation, and in the west-northwest by the Pantanal wetlands. It stretches from equatorial zones to 23° south latitude (Motta et al. 2002). The Cerrado is usually classified in five physiognomies according to the proportion of trees and grasses. According to Coutinho (1978, 2006) this biome consists of one grassland (campo limpo), three savannic vegetations (Campo Sujo, Campo Cerrado and Cerrado *stricto sensu*) and one woodland vegetation (Cerradão).

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Deeper Latosols in the Cerrado cover extensive plateaus and gentle slopes, where Fe oxides and gibbsite contents are higher than in wetter Brazilian regions such as the Amazon. However, Cerrado soils can be also very shallow, with nearly no A horizon and often with low permeability in more broken, undulating reliefs, where the underlying substrate generally consists of nutrient-poor pelitic rocks (Resende et al. 2002).

The physical characteristics of Latosols are generally good, with high aggregate stability due to their oxidic character. Clay aggregates are stabilized by high amounts of Fe oxide and gibbsite coupled with organic matter (OM) (Schaefer et al. 2004). This strong stability allows good water and air movement associated with low resistance to root penetration. The soil is also less prone to erosion, with stable aggregates (Motta et al. 2002).

In spite of the good physical characteristics of Latosols, the availability of plant nutrients is low, especially regarding P, Ca^{2+}, K and micronutrients. Exchangeable Al^{3+} concentration is high in many Latosols, being generally toxic to less tolerant plants. For native vegetation, the low concentration of certain nutrients such as Ca^{2+}, P, S and N prevents the use of photosynthetic carbohydrates that accumulate in certain structures (Arens 1963). Due to the morphological properties determined by the edaphic attributes, this vegetation was classified as scleromorphous oligotrophic (Ferri 1977).

Latosols of Cerrado are generally well supplied with water, and groundwater is located few meters below the surface, whereas water deficiency is only observed in the upper two meters during the dry season. As in other savanna ecosystems, the occurrence of an indurated laterite (ironstone) layer is quite common at subsurface or surface level (Rizzini 1997), especially in the plateau borders.

The distribution of plant physiognomies is rather difficult to understand due to generally dystrophic soil properties with very low nutrient concentrations. However, within each community, plant species populations are consistently correlated with aluminum and calcium content, indicating a differentiated competitive potential (Furley and Ratter 1988, Haridasan et al. 1997, Oliveira-Filho 1989, Ratter 1971, Silva Junior et al. 1987).

A number of questions that involve soil and vegetation are quite complex and still unanswered. Some studies emphasize the influence of soil properties on the presence of a particular physiognomy on the one hand, and, on the other, the influence of the floristic composition on soil formation itself (Kellman 1979).

This study was conducted in the Paraopeba National Reserve and aims to classify and to evaluate the soils in the studied area, as well as verify the relationship between the soil and the vegetation. The relationship between soil and vegetation (physiognomy, floristic and structure) was evaluated by testing the following hypotheses: 1) under woodland physiognomies (Cerradão) the soil fertility is higher and the Al^{3+} content lower; 2) open savanna occurs only in areas with higher Al^{3+} content.

MATERIAL AND METHODS

STUDY AREA

This study was conducted in Paraopeba National Reserve, in the state of Minas Gerais, Brazil. FLONA is a Sustainable Use Conservation Unit, according to the Brazilian National System of Conservation Units (SNUC 2000). The geographic coordinates of Paraopeba National Reserve are 19°16'S 44°23'W, and ranges from 734 m a.s.l. in the south to 750 m a.s.l. in the north (Fig. 1). The regional climate is humid tropical, with rainy summers and dry winters (Fig. 2).

VEGETATION SAMPLING AND ANALYSIS

A phytosociological study of the tree-shrub layer was performed employing the fixed area method (Mueller-Dombois and Ellenberg 1974). Five

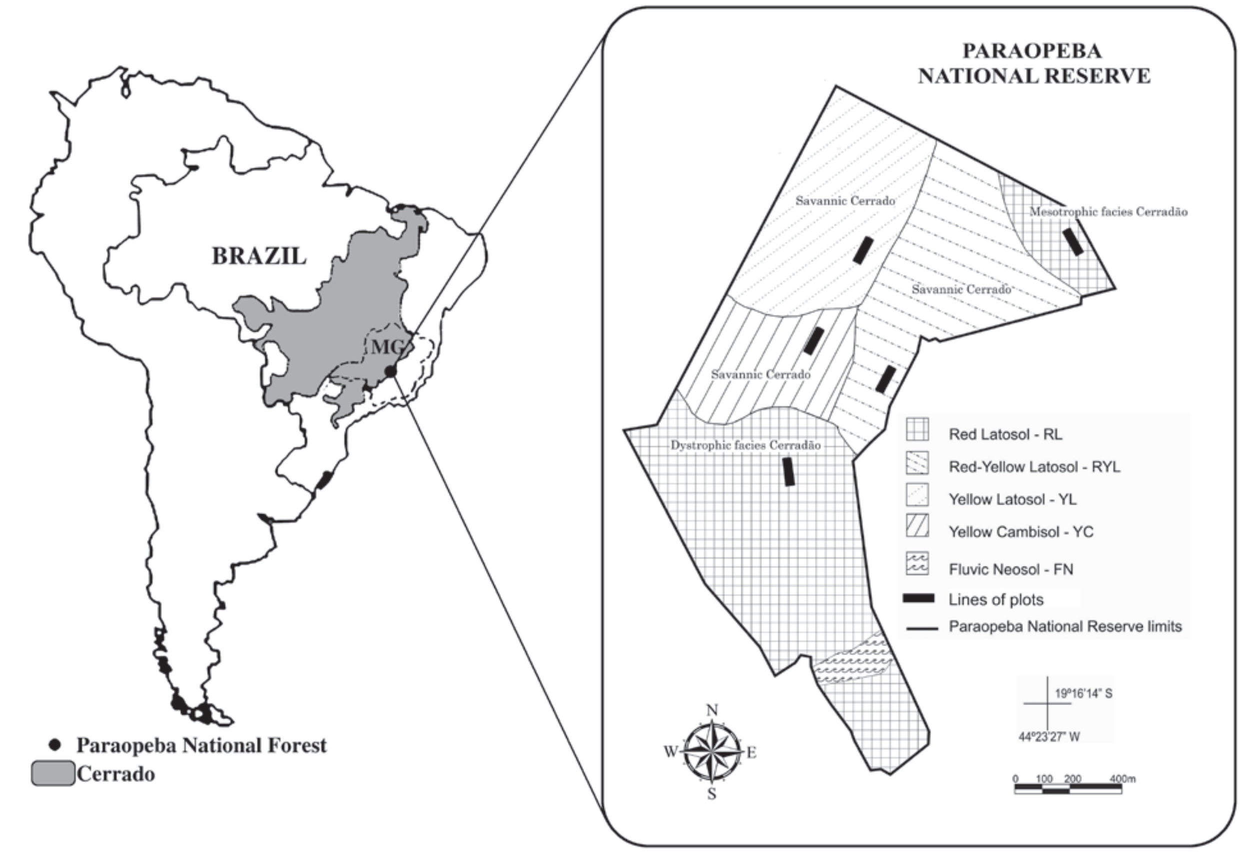

Figure 1 - Location of Paraopeba National Reserve in South America (WGS 84).

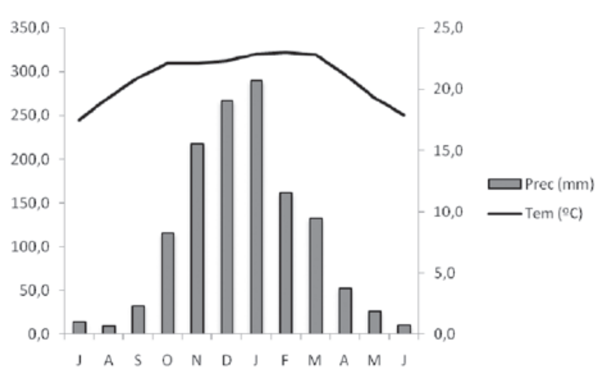

Figure 2 - Climatic diagram of Sete Lagoas, Minas Gerais state, the nearest climatic station to Paraopeba National Reserve (40 km). The columns show the mean monthly precipitation, and the continuous line represents the mean monthly temperature.

plots of 20 m x 100 m were allocated for the sampling, in which all the woody individuals with stem perimeter ≥ 10 cm at ground level were sampled. The plots were distributed in two different physiognomies (Cerrado *Stricto Sensu* and Cerradão). For statistical analysis the phytossociolocal parameters were calculated for five subplots (20 x 20 m) per site. These subplots represent subdivisions of the big plots (20 x 100 m). The study of the pedo-vegetational gradient was conducted using five environments with rather distinct characteristics: 1) Distrophic Cerradão on Red Latosol; 2) Mesotrophic Cerradão on Red Latosol; 3) Dense Cerrado *senso stricto* on Yellow Red Latosol; 4) Cerrado *senso stricto* on typical Yellow Latosol and 5) Cerrado *senso stricto* on Haplic Cambisol Tb Dystrophic.

Soil Sampling and Analysis

For this study, five soil profiles were selected and opened (100 cm wide x 150 cm long x 150 cm deep) in different areas, in order to represent all types of

Cerrado soils. The soils were classified according to the Brazilian System of Soil Classification (Embrapa 2006). For the chemical and physical analyses, soil samples were collected at every 10cm down to a depth of 30 cm, and from there downwards at every 20 cm to a depth of 150 cm, in total nine samples per profile. Color, detailed morphologic characteristics and total P contents were determined for samples from the layers 0-20 cm and 40-60 cm.

In addition to the five soil profiles, 25 subsurface soil samples (0-10 cm) were collected – five at each site.

The soil samples taken for chemical and physical analyses were air-dried and sieved to 2 mm. In the fraction < 2 mm, all physical and chemical soil properties were determined in the soil laboratory at the Universidade Federal de Viçosa. Soil color was determined by the Munsell color chart, and total P in clay was determined by sulphuric acid extraction.

Soil and Vegetation Gradients

The Spearman Rank Correlation Coefficient (rs) was used to verify the hypothesis that floristic-sociological parameters, such as basal area, species richness and density, in each of the phytophysiognomies are correlated with soil attributes (Al^{3+}, Ca^{2+}, P, K and the sum of bases). The 25 subsurface soil samples were used for this purpose.

The phytophysiognomies were subjectively ordered according to the density of their vegetation, in order to evaluate its correlation with soil variables, and assigned a number from one to four; 1: open vegetation (Cerrado *S. S.* under YL and C), 2: intermediate (Dense Cerrado S. S.), 3: closed vegetation (Dystrophic Cerradão), and 4: very closed vegetation (Mesotrophic Cerradão).

In addition to testing the hypotheses, a principal component analyses (PCA) was performed in order to gain more insight into the soil characteristics, using soil variables from the 25 subsurface soil samples: pH – active acidity; P – phosphorus; K – potassium; Ca^{2+} – exchangeable calcium; Mg^{2+} – exchangeable magnesium; SB – sum of bases; t – effective cation exchange capacity; T – cation exchange capacity for pH 7; V – base saturation; m – aluminum saturation; OM – organic matter; and P-rem – remaining phosphorus. The PCA was performed using PCORD (Mccune and Mefford 1997).

RESULTS

In the FLONA of Paraopeba 4,156 individuals were found altogether in the five sites. The richness was 132 species distributed in 47 families. Of the 132 sampled species, 14 were considered indifferent to the pedological conditions, since they were present in all the studied areas: *Acosmium dasycarpum* (Vogel) Yakovlev, *Alibertia edulis* (Rich.) A. Rich. ex DC., *Bowdichia virgilioides* Kunth, *Erythroxylum sp*, *Erythroxylum suberosum* A. St.-Hil., *Eugenia dysenterica* DC., *Guapira noxia* (Netto) Lundell, *Machaerium opacum* Vogel, *Myrcia lingua* (O. Berg) Mattos & D. Legrand, *Ouratea castaneifolia* (DC.) Engl., *Qualea grandiflora* Mart., *Qualea multiflora* Mart., *Roupala montana* Aubl., *Zeyheria montana* Mart. A summary of the floristic-structural analysis is given in Table I, showing clearly some fundamental differences between the different vegetations, for example regarding to diversity and basal area. A more detailed vegetation analysis can be found in Neri et al. (2012).

The phytophysiognomic gradient observed in Paraopeba National Reserve seems to be directly related to differences in the soil (Fig. 3). In the Mesotrophic Cerradão, where the highest soil fertility is found (Table II), taller plants showed a more closed canopy, associated with the absence of the graminoid layer. On the other hand, the Dystrophic Cerradão exhibited a more open canopy with sparse graminoid layer, associated with lower soil fertility (Table IV), although both phytophysiognomies are found on a Red Latosol.

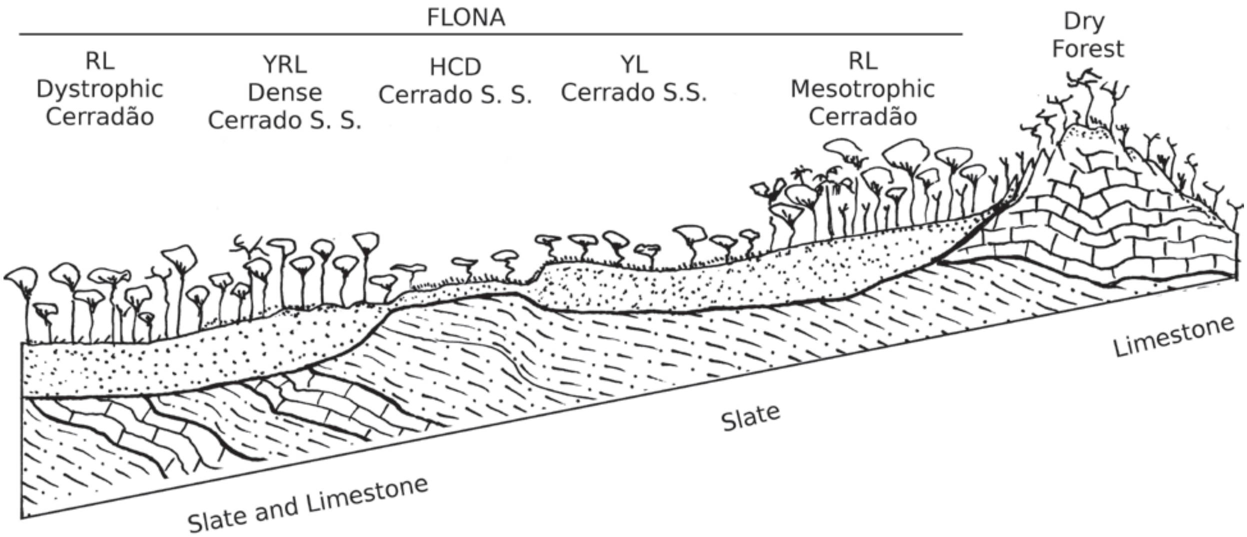

Figure 3 - Schematic geomorphologic-soil-vegetation profile. All Cerrado (savanna) and Cerradão (woodland) phytophysiognomies occur in Paraopeba National Reserve whereas Dry Forest is at northeast bound neighboring site. RL – Red Latosol, RYL – Red-Yellow Latosol, YL – Yellow Latosol, C – Cambisol.

TABLE I
Data from the analysis of the vegetation structure in the FLONA of Paraopeba, MG, Brazil.

Area	H'	J'	S'	Fam.	NI	BA
D. C.	3.26	0.80	58	32	556	25.49 m^2\ha
M. C	3.26	0.76	72	36	958	40.18 m^2\ha
C-YRL	3.54	0.83	71	38	1,187	38.46 m^2\ha
C-YL	3.35	0.81	61	25	673	19.27 m^2\ha
C-HCD	2.28	0.72	53	24	782	19.32 m^2\ha

H': Shannon diversity; J': equability, S': number of species, F: family, NI: number of individual, BA: basal area. Areas: D.C.- Distrophic Cerradão on Red Latosol; M.D.- Mesotrophic Cerradão on Red Latosol; C-YRL - Dense Cerrado *senso stricto* on Yellow Red Latosol; C-YL - Cerrado *senso stricto* on typical Yellow Latosol e C-HCD - Cerrado *senso stricto* on Haplic Cambisol Tb Dystrophic.

The most open Cerrado areas are typical savanna forms, and were observed on both Yellow Latosol and Cambisol (Tables VIII and X). The most remarkable difference between observations made on the two soils is the dominance of *Miconia albicans* (Sw.) Steud. in the savannic Cerrado developed on the shallower Cambisol. Another study site was on Red-Yellow Latosol (Table VI) in closed savanna (Cerrado), whose denomination refers to the presence of a higher tree density. In addition to higher tree density, trees are also taller than those in the Yellow Latosol and Cambisol, although both were classified as savanna (Cerrado).

Red Latosol under Mesotrophic Cerradão

Mesotrophic Cerradão is a woodland with canopy height varying from 8 to 13 m. Cyperaceae and Poaceae are absent in the understory, where the flora is different from the Dystrophic Cerradão. In the Mesotrophic Cerradão, the most abundant species are *Luehea divaricate* Mart., *Magonia pubescens* A. St.-Hill., *Myracrodruon urundeuva* Allemão and *Dilodendron bipinnatum* Radlk.

In the Mesotrophic Cerradão, where the vegetation shows a transitional feature between Tropical Dry Forests and savannic Cerrado, the content of available P at soil depth 0-20 cm was the highest of all the soil samples. Available P values steadily decreased down to 70 cm depth, at which the remaining P values were also very low, indicating gibbsite-rich and Fe-oxide mineralogy, with high P adsorption capacity. Available P values in this environment were higher than in the Dystrophic Cerradão on Red Latosol with taller vegetation.

The highest total P value for clay was found in the soil of Mesotrophic Cerradão at a depth of 0-20 cm, whereas in the 40-60 cm layer the value was lower than in Dystrophic Cerradão (Table II).

Organic matter contents were high at 0-10 cm depth, tending to be uniformly high down to 150 cm, indicating intense and deep pedobioturbation by micro and mesofauna (worms, ants and termites)

TABLE II
Chemical attributes of Red Latosol (RL) under Mesotrophic Cerradão (woodland) in Paraopeba National Reserve.

RL	pH	Available P	Total P	K	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	BS	CEC	V	m	OM	P rem	Zn	Fe	Mn	Cu
cm	H_2O	mg/kg				$cmol_c/dm^3$					%		dag/kg	mg/L	mg/dm^3			
0-10	6.74	1.3	**284.12**	149	13.20	1.04	0.00	2.2	14.62	16.82	86.9	0.0	10.14	24.7	2.47	20.0	49.8	0.40
10-20	6.43	2.4		94	7.58	0.74	0.00	2.2	8.56	10.76	79.6	0.0	8.55	22.1	1.44	26.2	9.4	0.50
20-30	5.28	0.5		53	1.96	0.39	1.71	6.9	2.49	9.39	26.5	40.7	8.17	13.9	1.31	29.6	4.8	0.54
30-50	5.06	0.2	**198.90**	20	0.39	0.05	2.86	3.9	0.49	4.39	11.2	85.4	7.92	7.9	0.69	30.2	3.1	0.64
50-70	5.11	0.2		10	0.19	0.02	2.76	6.1	0.24	6.34	3.8	92.0	7.48	6.7	0.67	12.7	1.6	0.20
70-90	5.13	0.0		10	0.05	0.00	2.29	5.2	0.08	5.28	1.5	96.6	7.29	3.8	0.97	14.6	1.7	0.12
90-110	5.00	0.0		9	0.02	0.00	2.38	5.0	0.04	5.04	0.8	98.3	7.16	2.9	0.89	14.4	1.3	0.12
110-130	4.89	0.0		9	0.06	0.00	1.81	4.6	0.08	4.68	1.7	95.8	7.10	1.8	0.66	19.0	1.1	0.19
130-150	4.88	0.0		8	0.01	0.00	1.81	4.7	0.03	4.73	0.6	98.4	7.10	2.1	0.40	14.6	1.1	0.11

The total P values were obtained at 0-20cm and 40-60cm depths. OM: organic matter; CEC: cation exchange capacity; BS: bases sum; P-rem: remaining P; m=% Al saturation; v: bases saturation.

incorporating C to higher depths, and increasing carbon distribution within the soil (Schaefer 2001). Similarly, the total CEC values were higher (down to 40 cm) in this environment and in the Dystrophic Cerradão compared to the others, indicating a considerable contribution of organic matter to the chemical charge in Latosols under Cerradão (Table II).

Ca^{2+} contents are high only at the 0-20 cm depth, thereafter decreasing sharply with depth. This suggests that cycling in the surface layer is essential for plant growth, and that these soils do not have any Ca^{2+} reserve in the mineral fraction. On the other hand, exchangeable Al^{3+} saturation reaches over 85% of the CEC below 30 cm (Table II).

The soil color was 5YR 4/6 in the 0-20 cm layer, and 2.5YR 4/8 in 40-60 cm layer. The soil is clayey throughout the profile, with clay contents varying from 43 dag/kg in the 0-10 cm layer, to 66 dag/kg in the 50-70 cm layer. The high silt contents do not indicate primary minerals, but rather the presence of pseudo-silt, which represents the clay fraction that could not be dispersed by the texture analysis method used here (Table III) (Schaefer et al. 2008).

RED LATOSOL UNDER DYSTROPHIC CERRADÃO

Dystrophic Cerradão is a woodland formation but differs from the Mesotrophic Cerradão regarding the most abundant species: *Bowdichia virgilioides* Kunth, *Styrax camporum* Pohl, *Xylopia aromatica* (Lam.) Mart., *Roupala Montana* Aubl., *Plathymenia reticulate* Benth., and *Brosimum gaudichaudii* Trécul.

The available P contents in the Dystrophic Cerradão were higher at 0-20 cm depth, decreasing drastically beyond 20 cm depth. Total P contents at both depths were high compared to the other

TABLE III

Physical and morphological traits of Red Latosol (RL) under Mesotrophic Cerradão (woodland) in Paraopeba National Reserve.

RL	Coarse sand	Fine sand	Silt	Clay	Texture	Munsell	Morphology
cm	dag/kg					color	
0-10	2	3	52	43	Silty Clayey		
10-20	2	3	44	51	Silty Clayey	5YR 4/6	0-20cm: moderate, medium size subangular blocky and moderate medium microgranular. Small size organic matter blocky was found.
20-30	1	3	36	60	Very Clayey		
30-50	1	3	39	57	Clay		
50-70	1	4	29	66	Very Clayey	2.5YR 4/8	40-60cm: weak, small to medium size, sub-angular blocky structure, moderate to strong, with microgranular.
70-90	1	2	33	64	Very Clayey		
90-110	1	2	38	59	Clay		
110-130	1	3	38	58	Clay		
130-150	1	3	36	60	Very Clayey		

Color and morphological traits were obtained at 0-20cm and 40-60cm depths.

soils, indicating greater P reserves (Table IV). The organic matter values were higher than in the Mesotrophic Cerradão, particularly at the 0-10 cm horizon. Similar to the Mesotrophic Cerradão, the CEC values were higher at 0-20 cm and decreased gradually downwards. However, at the same depth, the exchangeable Al^{3+} content was higher. In the 10-20 cm layer, the Al^{3+} content was also higher than the others, except in Yellow Latosol with savannic Cerrado (Table IV).

TABLE IV

Chemical attributes of Red Latosol (RL) under Dystrophic Cerradão (woodland) in Paraopeba National Reserve.

RL	pH	Available P	Total P	K	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	BS	CEC	V	m	OM	P rem	Zn	Fe	Mn	Cu
cm	H_2O	mg/kg				$cmol_c/dm^3$					%		dag/kg	mg/L	mg/dm^3			
0-10	4.22	1.2	**253.95**	26	0.08	0.05	4.09	14.8	0.20	15.00	1.3	95.3	11.47	10.7	0.56	45.3	7.8	0.50
10-20	4.35	0.7		17	0.00	0.01	2.86	10.1	0.05	10.15	0.5	98.3	9.32	9.6	0.23	28.8	5.1	0.50
20-30	4.36	0.5		10	0.00	0.00	2.29	9.3	0.03	9.33	0.3	98.7	9.00	8.0	0.19	29.1	5.5	0.58
30-50	4.56	0.3	**202.05**	6	0.00	0.00	2.00	8.5	0.02	8.52	0.2	99.0	8.68	9.4	0.45	23.3	5.9	0.56
50-70	4.66	0.0		7	0.00	0.00	1.90	6.9	0.02	6.92	0.3	99.0	8.17	8.0	0.67	11.8	5.0	0.85
70-90	4.83	0.0		1	0.00	0.00	1.81	6.3	0.00	6.30	0.0	100.0	7.98	7.0	0.99	9.0	3.8	0.35
90-110	4.88	0.0		1	0.00	0.00	1.62	5.3	0.00	5.30	0.0	100.0	7.73	5.0	0.07	7.8	3.4	0.27
110-130	5.04	0.0		1	0.00	0.00	1.33	5.0	0.00	5.00	0.0	100.0	7.67	4.2	0.00	6.3	3.0	0.19
130-150	5.09	0.0		1	0.00	0.00	1.14	4.7	0.00	4.70	0.0	100.0	7.54	3.8	0.00	6.4	2.4	0.22

The total P values were obtained at 0-20cm and 40-60cm depths. OM: organic matter; CEC: cation exchange capacity; BS: bases sum; P-rem: remaining P; m=% Al saturation; v: bases saturation.

The soil of the Dystrophic Cerradão was characterized as Red Latosol with color ranging from 5YR 4/6 at 0-20 cm depth to 2.5YR 4/6 between 40-60 cm. The soil texture is very clayey throughout the profile, with clay contents varying from 74 dag/kg at 0-10 cm to 85 dag/kg 70-90 cm (Table V).

Red-Yellow Latosol under Closed Savannic Cerrado

Closed savannic Cerrado is a type of savannic Cerrado with greater density of woody plants to the detriment of the graminoid layer. *Platypodium elegans* Vogel, *Vochysia tucanorum* Mart., *Alibertia edulis* (Rich.) A. Rich. ex DC., *Xylopia aromatic* (Lam.) Mart., and *Roupala montana* Aubl. were particularly abundant in this vegetation.

TABLE V
Physical and morphological attributes of Red Latosol (RL) under Dystrophic Cerradão (woodland) in Paraopeba National Reserve.

RL	Coarse sand	Fine sand	Silt	Clay	Texture	Munsell	Morphology
cm		dag/kg				color	
0-10	3	2	21	74	Very Clayey		
10-20	2	2	19	77	Very Clayey	5YR 4/6	0-20cm: weak, small to medium size, subangular blocky and strong very small microgranular
20-30	2	2	18	78	Very Clayey		
30-50	1	2	20	77	Very Clayey		
50-70	2	2	15	81	Very Clayey	2.5YR 4/6	40-60cm: weak, small to medium size, sub-angular blocky structure, moderate to strong, with small microgranular.
70-90	1	2	12	85	Very Clayey		
90-110	2	2	18	78	Very Clayey		
110-130	1	2	19	78	Very Clayey		
130-150	2	2	17	79	Very Clayey		

Color and morphological traits were obtained at 0-20cm and 40-60cm depths.

Although the Red-Yellow Latosol occurs under denser and taller Cerrado (savanna) vegetation, the available P content was the lowest of the sites, whereas horizontally the highest P content was found at 90-110 cm depth. In spite of the lower available P content in this soil, the total P was higher than in the savanna (Cerrado) on Yellow Latosol, indicating greater non-available P reserve (Table VI). The organic matter amounts were low, and followed the same trend of other soils in the area. Similarly, the CEC values were higher in the 0-30 cm layer, decreasing downwards, and reaching values lower than in other soils, indicating an oxidic minerology. The available Ca^{2+} contents in this soil were low and concentrated at the 0-10 cm depth, with values higher than those in the Dystrophic Cerradão. Exchangeable Al^{3+} was relatively uniform down to 30 cm, and dropped markedly downwards, due to gibbsite formations and Al^{3+} insolubilization.

The soil color at 0-20 cm depth was 5YR 5/6, and 5YR 5/8 at 40-60 cm with a very clayey texture throughout (Table VII).

Yellow Latosol under Cerrado (Savanna)

This Cerrado is characterized by well-defined graminoid, shrub and woody strata on a typical Yellow Latosol. The most abundant species were *Pera glabrata* (Schott) Poepp. ex Baill., *Trichilia pallid* Sw., *Salvertia convallariodora* A. St.-Hil., *Miconia albicans* (Sw.) Steud., *Eugenia dysenterica* DC. and *Byrsonima cydoniifolia* A. Juss.

TABLE VI
Chemical attributes of Red Yellow Latosol (RYL) under closed savannic Cerrado in Paraopeba National Reserve.

RL	pH	Available P	Total P	K	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	BS	CEC	V	m	OM	P rem	Zn	Fe	Mn	Cu
cm	H_2O	mg/kg				$cmol_c/dm^3$					%		dag/kg	mg/L	mg/dm^3			
0-10	4.77	0.3	**211.26**	90	0.20	0.43	2.57	8.8	0.86	9.66	8.9	74.9	9.19	14.7	0.42	66.6	2.4	0.57
10-20	4.79	0.0		71	0.02	0.09	2.29	7.5	0.29	7.79	3.7	88.8	8.43	12.8	0.30	38.3	1.7	0.48
20-30	4.74	0.0		32	0.00	0.00	2.29	6.3	0.08	6.38	1.3	96.6	8.11	12.7	0.15	24.0	1.2	0.45
30-50	4.76	0.0	**186.31**	20	0.00	0.00	1.81	5.5	0.05	5.55	0.9	97.3	7.86	9.5	0.29	20.8	1.3	0.89
50-70	4.89	0.0		17	0.00	0.00	1.62	4.1	0.04	4.14	1.0	97.6	7.54	8.5	0.14	11.1	1.1	0.19
70-90	4.91	0.0		13	0.00	0.00	1.33	4.4	0.03	4.43	0.7	97.8	7.41	5.8	0.26	10.4	0.5	0.21
90-110	4.99	0.8		7	0.00	0.00	1.05	3.8	0.02	3.82	0.5	98.1	7.35	4.0	0.15	17.1	0.5	0.20
110-130	5.08	0.0		5	0.00	0.00	0.86	3.3	0.01	3.31	0.3	98.9	7.22	3.1	0.00	9.5	0.3	0.13
130-150	5.24	0.0		5	0.00	0.00	0.76	2.2	0.01	2.21	0.5	98.7	7.16	3.4	0.00	16.3	0.5	0.19

Color and morphological traits were obtained at 0-20cm and 40-60cm depths. OM: organic matter; CEC: cation exchange capacity; BS: bases sum; P-rem: remaining P; m=% Al saturation; v: bases saturation.

TABLE VII
Physical and morphological traits of Red Yellow Latosol (RYL) under closed savannic Cerrado in Paraopeba National Reserve.

RL	Coarse sand	Fine sand	Silt	Clay	Texture	Munsell	Morphology
cm		dag/kg				color	
0-10	2	3	28	67	Very Clayey		
10-20	2	3	27	68	Very Clayey	5YR 5/6	0-20cm: moderate, medium size, subangular blocky and moderate medium microgranular
20-30	2	3	27	68	Very Clayey		
30-50	2	3	26	69	Very Clayey		
50-70	1	4	30	65	Very Clayey	5YR 5/8	40-60cm: weak to moderate, small to medium size, sub-angular blocky structure, with moderate –strong, with small microgranular.
70-90	1	3	28	68	Very Clayey		
90-110	2	2	29	67	Very Clayey		
110-130	2	2	29	67	Very Clayey		
130-150	2	2	30	66	Very Clayey		

Color and morphological traits were obtained at 0-20cm and 40-60cm depths.

The available P contents in this environment were very low, even in the surface layer at 0-10 cm depth. The total P contents in this environment were the lowest, in the 0-20 cm layer as well as in the 40-60 cm one, indicating negligible P reserves (Table VIII), compared with the Red-Yellow Latosol. The Al^{3+} content in Cerrado (Savanna) on Yellow Latosol was high at 0-10 cm depth, and decreased down to 90 cm; from this depth downwards, Al^{3+} contents increased gradually to 150 cm (Table VIII).

The soil color was 10YR 7/6 at 0-20 cm depth, and 10YR 7/8 at 40-60 cm. The texture class in this environment varied from clay-silt to very clayey (Table IX).

TABLE VIII

Chemical attributes of Yellow Latosol (YL) under savannic Cerrado in Paraopeba National Reserve.

RL	pH	Available P	Total P	K	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	BS	CEC	V	m	OM	P rem	Zn	Fe	Mn	Cu
cm	H_2O	mg/kg				$cmol_c/dm^3$					%		dag/kg	mg/L	mg/dm^3			
0-10	4.77	0.7	**154.66**	69	0.13	0.10	3.62	7.4	0.41	7.81	5.2	89.8	8.55	18.7	0.37	63.9	9.1	0.98
10-20	4.69	0.3		50	0.00	0.00	3.43	6.9	0.13	7.03	1.8	96.3	8.05	14.7	0.50	31.7	1.4	0.65
20-30	4.83	0.1		47	0.00	0.00	3.14	6.1	0.12	6.22	1.9	96.3	7.92	13.5	0.47	22.9	1.0	0.58
30-50	4.97	0.0	**136.35**	22	0.00	0.00	2.57	4.6	0.06	4.66	1.3	97.7	7.54	13.5	0.62	13.3	0.7	0.23
50-70	5.02	0.1		12	0.00	0.00	2.19	4.4	0.03	4.43	0.7	98.6	7.35	8.6	0.37	7.6	0.5	0.17
70-90	5.18	0.0		12	0.00	0.00	1.81	3.9	0.03	3.93	0.8	98.4	7.16	5.8	0.38	6.0	0.2	0.13
90-110	5.18	0.0		10	0.00	0.00	2.86	4.7	0.03	4.73	0.6	99.0	7.22	5.0	0.28	7.9	0.3	0.19
110-130	5.13	0.0		18	0.00	0.00	3.24	5.0	0.05	5.05	1.0	98.5	7.16	6.2	0.00	8.6	0.3	0.17
130-150	5.04	0.0		18	0.00	0.00	4.67	6.3	0.05	6.35	0.8	98.9	7.10	4.9	0.88	7.7	0.2	0.20

Color and morphological traits were obtained at 0-20cm and 40-60cm depths. OM: organic matter; CEC: cation exchange capacity; BS: bases sum; P-rem: remaining P; m=% Al saturation; v: bases saturation.

TABLE IX

Physical and morphological traits of Yellow Latosol (YL) under savannic Cerrado in Paraopeba National Reserve.

RL	Coarse sand	Fine sand	Silt	Clay	Texture	Munsell	Morphology
cm		dag/kg				color	
0-10	2	3	53	42	Very Clayey	10YR 7/6	0-20cm: moderate, medium size, subangular blocky and moderate medium microgranular.
10-20	2	2	49	47	Very Clayey		
20-30	2	2	46	50	Very Clayey		
30-50	2	2	43	53	Very Clayey	10YR 7/8	40-60cm: weak to moderate, small to medium size sub-angular blocky structure, with moderate microgranular
50-70	2	2	37	59	Clayey		
70-90	2	2	42	54	Silty clay		
90-110	1	2	47	50	Silty clay		
110-130	1	1	45	53	Silty clay		
130-150	1	1	37	61	Very clayey		

Color and morphological traits were obtained at 0-20cm and 40-60cm depths.

CAMBISOL UNDER CERRADO (SAVANNA)

This environment is a savannic Cerrado with two well defined graminoid and woody strata. The most abundant woody species is *M. albicans*, known as an aluminum accumulator (Haridasan 2000a and Haridasan 2000b).

Compared to the Cerrado on Yellow Latosol, a savannic Cerrado without *Miconia* dominance, the available P content in the 0-10 cm layer was lower. On the other hand, the remaining P values were higher in the surface due to the effect of higher organic matter content. In subsurface, the remaining

P values dropped markedly, illustrating the strong degree of weathering of these acid soils. Total P contents in the clay fraction were higher than in Yellow Latosol and in Red Yellow Latosol (Table X). The organic matter contents were higher in the 0-20 cm horizon, as expected, with low and stable amounts from 20 down to 110 cm. This is thought to be evidence of strong pedobioturbation promoted by mesofauna in the Latosols under Cerrado (Schaefer 2001). Consistently, the highest CEC values were found in the 0-10 cm layer, owing to the effect of organic matter, and decreased with increasing depth.

The soil was classified as Dystrophic Cambisol. Soil color in the 0-20 cm layer was 10YR 7/6, and 7.5YR 7/8 in 40-60 cm, with a clayey texture down to 70 cm, changing to silt clay at 70-90 cm. From 90 cm downwards we observed the weathered pellitic rock (slate) with increasing silt amounts, ranging from 60 to 74 dag/kg (Table XI).

TABLE X

Chemical attributes of Cambisol (C) under savannic Cerrado in Paraopeba National Reserve.

RL	pH	Available P	Total P	K	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	BS	CEC	V	m	OM	P rem	Zn	Fe	Mn	Cu
cm	H_2O	mg/kg				$cmol_c/dm^3$					%		dag/kg	mg/L	mg/dm^3			
0-10	5.01	0.6	**221.37**	128	0.10	0.24	2.86	6.9	0.67	7.57	8.9	81.0	8.43	11.5	1.71	55.4	3.6	0.69
10-20	5.08	0.4		86	0.00	0.02	2.57	5.7	0.24	5.94	4.0	91.5	8.05	7.4	1.60	23.0	1.1	0.42
20-30	5.12	0.4		60	0.00	0.00	2.10	4.6	0.15	4.75	3.2	93.3	7.73	6.9	0.66	16.8	0.6	0.26
30-50	5.19	0.2	**188.94**	44	0.00	0.00	1.43	3.8	0.11	3.91	2.8	92.9	7.41	5.0	0.87	10.1	0.4	0.18
50-70	5.37	0.1		25	0.00	0.00	1.71	3.8	0.06	3.86	1.6	96.6	7.22	2.5	2.24	10.3	0.5	0.14
70-90	5.18	0.0		16	0.00	0.00	2.38	4.2	0.04	4.24	0.9	98.3	7.16	2.4	0.50	11.5	0.6	0.13
90-110	5.20	0.1		10	0.00	0.00	3.33	4.2	0.03	4.23	0.7	99.1	7.10	4.1	1.81	10.8	0.4	0.13
110-130	5.17	0.0		14	0.00	0.00	2.76	3.8	0.04	3.84	1.0	98.6	6.91	13.0	0.73	12.9	0.6	0.08
130-150	5.22	0.0		12	0.00	0.00	2.86	3.1	0.03	3.13	1.0	99.0	6.84	19.5	0.00	12.4	1.1	0.07

Color and morphological traits were obtained at 0-20cm and 40-60cm depths. OM: organic matter; CEC: cation exchange capacity; BS: bases sum; P-rem: remaining P; m=% Al saturation; v: bases saturation.

TABLE XI

Physical and morphological traits of Cambisol (C) under savannic Cerrado in Paraopeba National Reserve.

RL	Coarse sand	Fine sand	Silt	Clay	Texture	Munsell	Morphology
cm	dag/kg					color	
0-10	2	1	37	60	Very clayey		
10-20	2	1	37	60	Very clayey	10YR 7/6	0-20cm: moderate, medium size, subangular blocky and moderate medium microgranular.
20-30	2	0	36	62	Very clayey		
30-50	2	1	33	64	Very clayey		
50-70	1	0	34	64	Very clayey	10YR 7/8	40-60cm: moderate small size, sub-angular blocky structure, weak/moderate small microgranular
70-90	1	0	41	58	Silty clay		
90-110	1	1	60	38	Silty clay		
110-130	1	2	74	23	Silty		
130-150	0	2	70	28	Silty clay		

Color and morphological traits were obtained at 0-20cm and 40-60cm depths.

SOIL /VEGETATION GRADIENT

The Cerrado vegetation becomes thinner and shorter as the CEC decreases in the 0-10 cm soil layer in Paraopeba National Reserve. In other words, the transition from woodland cerradão to open savanna cerrado occurs along this gradient. However, for Al^{3+} the reverse is true: lower contents correspond to denser vegetation forms (Tables II, IV, VI, VIII and X).

In general, soil and vegetation variables presented a very close correlation (Table XII). In particular, it is possible to highlight the correlation between available P and phytophysiognomies (rs = 0.89) and between available P and basal area (rs = 0.72). Density (number of individuals) and richness present a positive correlation to K, Ca^{2+} and SB and a negative correlation to Al^{3+}.

TABLE XII

Spearman correlation between soil and vegetation variables.

	P	K	Ca^{2+}	Mg^{2+}	SB	Al^{3+}
Ph	0.89	-	-	-	-	-
BA	0.72	0.42	0.47	-	0.51	-0.50
NI	-	0.65	0.52	-	0.68	-0.70
NS	-	0.44	0.49	0.61	0.58	-0.57

P – available phosphorus; K – potassium; Ca^{2+} – exchangeable calcium; Mg^{2+} – exchangeable magnesium; SB – sum of bases; Al3+ – aluminum; Ph – Phytophysiognomies; BA – basal area; NI – number of individuals; NS – number of species.
The numbers present in the table are the ones that were significant with P values < 0.05.

The results of the PCA using the subsurface soil variables showed a high variance, and a clear separation into three groups (Figure 4). The first group correlated with high soil fertility, Mesotrophic Cerradão; the second group was correlated with

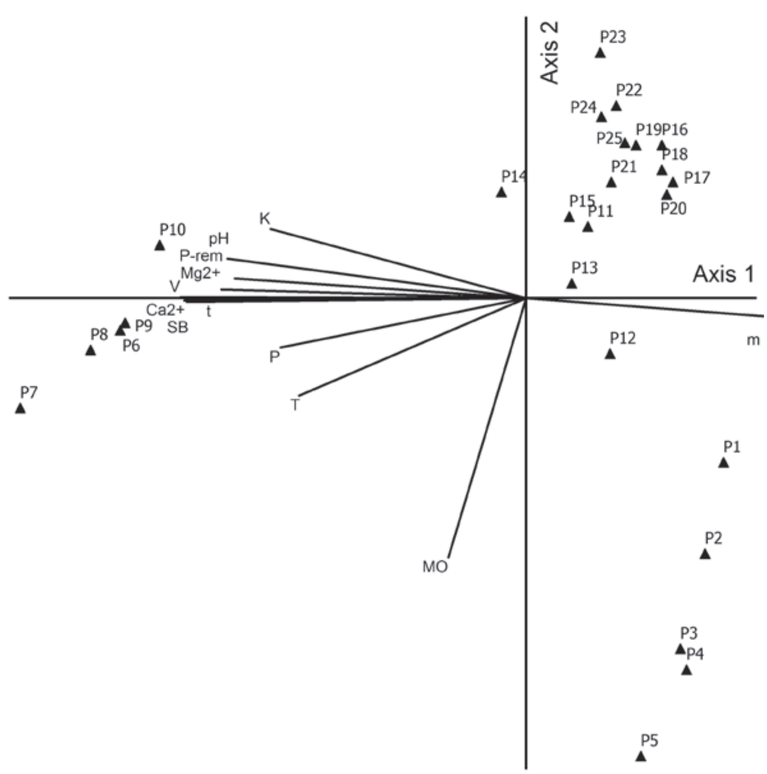

Figure 4 - Ordination of variables of soil in Paraopeba Forest Reserve, state of Minas Gerais, Brazil. P1 – P5 Dystrophic Cerradão; P6 – P10 Mesotrophic Cerradão; Cerrado *sensu stricto* on Red Yellow Latosol: P11, P12, P13, P14, P15; Cerrado *sensu stricto* on Yellow Latosol: P16, P17, P18, P19, P20; Cerrado *sensu stricto* on Cambisol: P21, P22, P23, P24, P25. (pH – active acidity; P – phosphorus; K – potassium; Ca2+ –exchangeable calcium; Mg2+ – exchangeable magnesium; SB – sum of bases; t – effective cation exchange capacity; T – cation exchange capacity for pH 7; V – base saturation; m – aluminium saturation; OM – organic matter; P-rem – remaining phosphorus).

organic matter (OM), Dystrophic Cerradão; and the third group correlated with aluminum, the two areas of Cerrado s.s. The percentage of variance accounted for by the first axis was 81% and the second axis was 13.6%.

These results partially contradict the first hypothesis, since Mesotrophic Cerradão appeared to be related to high soil fertility and low aluminum content, whereas Dystrophic Cerradão does not. However the open areas of Cerrado were correlated with high tenor of Al^{3+}, confirming the second hypothesis.

DISCUSSION

The soils in all environments of Paraopeba National Reserve were found to be clayey and weathered. In comparison to other soils under Cerrado in Minas Gerais, the low percentage of sand in the soils differs remarkably from the pedoenvironments of medium-texture Dystrophic Red-Yellow Latosols studied in northwestern Minas Gerais, whereas the texture is similar to that of Dystrophic Dark Red Latosols (CETEC 1981).

Available P values found in the soils were low, compared to the values found in the Cerrado vegetation in Biological Reserve of Mogi Guaçu, in the state of São Paulo (Batista and Couto 1990), where values of 17.5 ppm at 0-20 cm and 17.0 ppm at 20-40 cm were found. Oliveira-Filho and Martins (1986) found values for Cerrado on quartzite in the Chapada dos Veadeiros, which are very similar to those found for the areas of Cerrado in Paraopeba National Reserve. The available P values in Paraopeba National Reserve are also lower than the less clayey Latosols of northwestern Minas Gerais (CETEC 1981).

Total CEC values were higher for the two woodland environments, the Mesotrophic and the Dystrophic Cerradão. Comparable values were observed in Cerrado environments on Dystrophic Red-Yellow Latosol and three areas of Dystrophic Dark Red Latosol in northwestern Minas Gerais (CETEC 1981). In other soils studied by CETEC (1981), lower CEC value, associated with yellowish and red-yellowish color, were found. CEC values in the soil under Cerradão in FLONA were closely related to the Cerrado soils studied by Sans et al. (1979), Batista and Couto (1990) and Souza (2004).

The exchangeable Ca^{2+} concentrations were very low, with values typically < 0.20 $cmol_c/dm^3$, in the studied areas, except for the Mesotrophic Cerradão. According to CETEC (1981), Ca^{2+} contents in soils under Cerrado were higher in NW Minas Gerais than in the Cerrado of FLONA in Paraopeba National Reserve.

Al^{3+} appears to be an important attribute in Cerrado ecosystems, since high concentrations seem to favor some species to the detriment of others (Neri et al. 2012, Furley and Ratter 1988). Compared to Cerrado areas elsewhere, a clear difference was observed from Goodland (1969) in Triângulo Mineiro. Goodland found lower values (means varying from 0.71 to 0.76 $cmol_c/dm^3$) than were found in Paraopeba National Reserve. These differences are attributable to the clay/silt rich parent material (slate) with high natural Al^{3+} content found in Paraopeba National Reserve, unlike soils in Triângulo Mineiro, derived from Al-poor sandstones or basalts, or of northwestern Minas Gerais, derived from sandstones and sandy-clayey sediments.

Ca^{2+}, Al^{3+}, P and pH contents appear to influence the physiognomy and structure of the vegetation. High Al^{3+} concentrations in the soils of Dystrophic Cerradão and Cerrado on Cambisol favored the development of species such as *M. albicans*. In the Mesotrophic Cerradão, where the Al^{3+} concentration was nearly zero in the surface layer (0-20 cm), this species was not found at all. On the other hand, several species such as *L. divaricata*, *D. bipinatum*, *Tabebuia roseoalba* (Ridl.) Sanddwith, *Guettarda viburnoides* Cham. & Schltdl. were found in richer soils, and they were not detected in the other environments.

The role of organic matter in negative charge (CEC) generation and nutrient retention in Cerrado soils is well-documented (Van Raij 1981), since the clay fraction of these Latosols is dominantly oxidic and kaolinitic. According to Goodland (1969) and Goodland and Ferri (1979), the low clay activity of soils of Triângulo Mineiro indicates that organic matter plays a more important role in plant nutrient supply than clay. In Paraopeba National Reserve, in spite of its higher clay percentage when compared to Triângulo Mineiro and northwestern Minas Gerais, organic matter has a greater influence on plant nutrient supply, since the soils are oxidic and with very low CEC.

Ca^{2+} and Mg^{2+} values varied considerably between the areas. In the Mesotrophic Cerradão, which appears to be influenced by the limestone outcrop occurring 200 m upslope (Fig. 3), the Ca^{2+} and Mg^{2+} contents were high and in sharply contrast not only with data of other areas, but also with values reported by Goodland (1969). The values found at 0-10 cm depth (14.24 cmolc/dm3), is comparable to the maximum value found by Goodland (1969) in Cerradão (woodland). The values of other areas studied in Paraopeba National Reserve were similar to those found in Triângulo Mineiro, though somewhat lower. Hence, a close link between soil and vegetation may be established for Mesotrophic Cerradão.

The variation of pH, Ca^{2+}, Al^{3+} in Cerradão also appeared to exert a strong influence on the floristic composition of this vegetation, in spite of being a woodland physiognomy. This corroborates data presented by Ratter (1971, 1992) and Ratter et al. (1973, 1977) for Mesotrophic Cerradão, where flora is quite different from other woodlands on dystrophic soils, due to the greater nutrient availability (mostly Ca2+). For example, *M. pubescens* and *D. bipinnatum*, cited as calcicoles by Furley and Ratter (1988), were also abundant in this environment. In addition, other species considered calcicoles (Furley et al. 1988) were found: *Aspidosperma subincanum* Mart. ex A. DC., *M. urundeuva*, *Astronium fraxinifolium* Schott ex Spreng., *Casearia rupestris* Eichler, *Pseudobombax tomentosum* (Mart. & Zucc.) Robyns and *Terminalia argentea* Mart.

The correlations between vegetation (basal area, density and richness) and soil observed in Paraopeba National Reserve corroborate some studies, but contradict others. Ribeiro et al. (1981) evidenced a positive influence of Al^{3+}, Ca^{2+}+Mg^{2+}, potassium, phosphorus content, and the percentage of aluminum saturation on vegetation biomass, as well as a negative influence of pH. However, our results corroborate Goodland and Ferri (1979), and other authors (Batista and Couto 1990, Bertoni et al. 2001), who found a negative correlation between exchangeable aluminum and basal area or biomass. Batista and Couto (1990) pointed out that the soil also influences species richness, whereas high Al^{3+} content and low pH exert a negative influence on species richness as well as tree density. These differences are ascribed to different geo-pedologic contexts, since Al^{3+} contents depend strongly on the parent material, and the plant toxicity depends on the form and activity in solution, which is highly variable among soils with different texture and mineralogy.

CEC, Ca^{2+} and Al^{3+} seem to influence the Cerrado phytophysiognomies of Paraopeba National Reserve. The CEC, total P and available P contents were relevant for the maintenance of woodland; the highest values were found in Cerradão (woodland) and the lowest in areas of Cerrado (savanna).

Exchangeable Al^{3+} seems to play a major role in the establishment of different Cerrado physiognomies in Paraopeba National Reserve since the correlation with the density, richness and basal area was negative and significant.

The relative uniformity of the organic matter across the horizons, due to pedobioturbation by soil mesofauna, illustrates the importance of biological agents in soil formation and nutrient cycling in the different Cerrado phytophysiognomies in Paraopeba National Reserve.

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RESUMO

Este trabalho foi conduzido na Floresta Nacional de Paraopeba. O objetivo desse estudo foi classificar e avaliar o solo, assim como verificar a influência dos atributos do mesmo na vegetação. Para isso, foram também testadas as seguintes hipóteses: 1) nas áreas de Cerradão a fertilidade é mais alta e os teores de alumínio são mais baixos; 2) os cerrados *stricto sensu* ocorrem nas áreas com altos teores de Al^{3+}. Para isso, os solos da FLONA foram mapeados e identificados, além da análise química e física dos solos de cinco perfis. O gradiente ambiental foi facilmente observado pela análise de componentes principais (PCA), onde as diferenças entres as áreas foram evidenciadas. A correlação de Spearman foi usada para verificar as hipóteses. A relação entre vegetação (área basal, densidade e riqueza) e solo (K, Ca^{2+}, e Al^{3+}) foi estatisticamente significante. As hipóteses foram aceitas, porém a hipótese 1 apenas parcialmente. As características do solo parecem ter uma influência nas fitofisionomias do Cerrado e também em sua estrutura. O fósforo disponível foi um importante fator para a manutenção da fisionomia de Cerradão, assim como o Al^{3+} que parece ter um papel importante no estabelecimento de diferentes fisionomias de Cerrado.

Palavras-chave: tolerância ao alumínio, savana brasileira, características edáficas, fertilidade do solo, gradiente solo-vegetação.

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