

Soil-Vegetation Relationship in Quartzitic and Ferruginous Brazilian Rocky Outcrops

Maria Cristina Teixeira Braga Messias ·
Mariangela Garcia Praça Leite ·
João Augusto Alves Meira Neto ·
Alessandra Rodrigues Kozovits ·
Ricardo Tavares

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Abstract *Campo rupestre* is a kind of Brazilian rocky outcrop with high biodiversity and many endemic and threatened species. It occurs mainly in the Espinhaço Range in a contact region between Cerrado and/or Caatinga and Atlantic Forest. The Espinhaço Range is recognized as a region with the highest floristic diversity in South America and with many endemic species, most of which are associated with rocky outcrop environments. These, among other peculiarities, recently granted the Espinhaço Range the status of Biosphere Reserve. The relationship between soil and vegetation was studied in *campo rupestre* areas with quartzite and itabirite rocks. Three habitats in both lithologies were defined by geomorphology as: 1. Slopes with grasslands; 2. Plateaus with grasslands and 3. Valleys with woody savannas. In each lithology, 30 plots (10 × 10 m), 10 in each habitat, were defined. The species and their respective coverage were recorded and soil was sampled to perform chemical and physical analyses. The analyzed soils were similar in being sandy, acidic and with low fertility. Nevertheless,

M. C. T. B. Messias (✉) · A. R. Kozovits
Departamento de Biodiversidade Evolução e Meio Ambiente (DEBIO), Universidade Federal de Ouro Preto, Campus Universitário, 35400-000 Ouro Preto, Minas Gerais, Brazil
e-mail: cristina@iceb.ufop.br
e-mail: cristinabotanica@gmail.com

M. G. P. Leite
Departamento de Geologia, Universidade Federal de Ouro Preto, Ouro Preto, Minas Gerais, Brazil

J. A. A. Meira Neto
Departamento de Biologia Vegetal, Universidade Federal de Viçosa, Viçosa, Brazil

R. Tavares
Departamento de Matemática, Universidade Federal de Ouro Preto, Ouro Preto, Minas Gerais, Brazil

they exhibited differences in chemical and physical properties. Altogether there were 272 species, belonging to 70 families. The canonical correspondence analysis of soil variables and species coverage showed a clear segregation of lithological sites due mainly to the exchangeable content of Ca, Cu, Mg, Mn and S; soil particle size – central tendency and sorting; and the percentage of silt, fine soil and bare rocks. A strong correlation between plant species coverage and soil properties was also found.

Keywords Ferruginous *campos rupestres* · Metalliferous soil · Plant-soil relationships · Rocky outcrop vegetation

Plant nomenclature Forzza et al. (2012)

Introduction

Mountain areas are recognized centers of endemism and diversity, particularly in the tropics (Sarmiento 2002). *Campo rupestre* is a kind of Brazilian montane savanna occurring mainly in the Espinhaço Range. The Espinhaço Range is recognized as one of the regions with the highest floristic diversity in South America, having more than 30 % of Brazil's endemic species, most of which are associated with rocky outcrop environments (Giulietti et al. 1997). These, among other peculiarities, recently granted the Espinhaço Range the status of Biosphere Reserve (UNESCO 2005). *Campo rupestre*, according to Harley and Simons (1986), defines the Brazilian rocky outcrop fields found most commonly on quartzite-sandstone substrate; although this terminology is used to refer to similar phytophysiognomies on other kinds of rocky substrate such as, granitic-gneiss (Queiroz et al. 1996) or itabirite (Mourão and Stehmann 2007). In the Quadrilátero Ferrífero, Southeastern Brazil, *campo rupestre* also occur frequently in itabirite rock areas, some with duricrusts, known as *cangas*. Quadrilátero Ferrífero is an area rich in economically valuable ores, mainly iron ore, subjected to irrecoverable degradation by opencast mining (Jacobi et al. 2007).

Every *campo rupestre* soil is sandy, shallow and poor in nutrients. However, the geology influences the content of nutrients and the level of toxic elements (Benites et al. 2007). In addition, geomorphology also changes the soil characteristics, like depth and drainage (Messias et al. 2011). For instance, seasonal waterlogging may be found in the plateaus (Messias et al. 2011), as well as the occurrence of rock pools or ephemeral small ponds in rock depressions (Jacobi et al. 2007), contrasting with the xeric environment in other kinds of landform. So, there are different communities in *campos rupestres*, depending on the environment features (Jacobi et al. 2007; Porembski 2007).

Even though many authors suggest that the flora in *campos rupestres* depends on the characteristics of the soil, little is known about that. Only one study correlating soil properties with species abundance in *campos rupestres* was found, but in a restricted area, with few types of habitat (Vincent and Meguro 2008). According to this study, there was a strong correlation between plant species abundance and soil properties, where the species distribution was determined mainly by nutrients and heavy metal contents, especially Cu, Zn and Pb. By comparing the soil analyses in

different ferruginous and quartzitic rocky outcrop sites (Meguro et al. 1994; Benites et al. 2007; Conceição et al. 2007; Vincent and Meguro 2008), remarkable differences were found in physical and chemical soil properties for both quartzite and ferruginous soils, suggesting the necessity of more research to clarify the relationship of vegetation and soil properties. Mining activities have caused great destruction to this still poorly known ecosystem, suppressing plant species or populations that evolved in such a particular environment (Jacobi et al. 2007). Soil-vegetation relationship studies are fundamental to establish conservation strategies, mainly criteria for the fragment conservation of these areas and also to support reclamation projects. This research aimed to investigate which soil features determine vegetation differences in different lithotypes (quartzite and itabirite) and landform habitats of *campos rupestres*.

Methods

Study Site

This study was carried out in the Municipalities of Ouro Preto (itabirite plots) at 20°10' S and 43°31' W and Mariana (quartzite plots) at 20°13' S and 43°24' W, Minas Gerais State, southeastern Brazil, varying from 890 to 1,250 m a.s.l. This area belongs to Samarco Mineração S.A. and is part of the Serra de Ouro Preto, South of Espinhaço Range, part of the Alegria synclinal. The ferruginous rocks belong to the Cauê Formation, of the Itabira Group and Minas Supergroup, while the quartzite belongs to the Maquiné Group, Rio das Velhas Supergroup (Dorr 1969). The climate according to Köppen is Cwb, i.e., mesothermic, with a rainy summer during November-March and a dry winter (Nimer 1989). The annual mean rainfall is 1,250 mm and the annual mean temperature is around 20°C. According to the Brazilian Soil Classification System (EMBRAPA 1999), the soil in these areas was classified as *Neossolos litólicos*, which corresponds to the Entisol order of the US Soil Taxonomy (USDA 1998) and to the Leptosols of the FAO soil classification system (FAO 1998).

The *campos rupestres* areas, with different kinds of rock (itabirite and quartzite), were stratified in three different habitats, defined by geomorphology as: 1. Sloped areas with bare rocks, near the mountain summit, with grasslands; 2. Plateaus, with no more than 10 % slope inclination, with grasslands; 3. Valleys or depressions in the lower and/or concave parts of the slopes, with woody savannas. In each lithology, thirty 10 × 10 m plots, ten in each habitat, were defined. The grasslands in the sloped areas, established on itabirite (ISG), showed bare rocks with patterns similar to banded iron formations (BIFs); typical of raw itabirite. The grasslands on the plateaus (IPG) showed duricrusts, developed by the lateritic chemical weathering of itabirite. The woody savannas on itabirite (IWS) also had *cangas* partially covered by colluvial soil. The sloped grassland areas on quartzite (QSG) showed a great amount of smooth bare rocks, with shallow soil occupying gaps between the rocks, or forming small pools in rock depressions. The grassland plateaus in the quartzitic areas (QPG) were comprised of a sandy shallow and continuous soil with almost no

bare rocks. The woody savannas on quartzite (QWS) presented sandy and colluvial soil, with occasional bare rocks.

Soil Analyses

Soil samples were collected in the rainy season. In each plot, three samples (0–10 cm deep) were randomly collected and mixed for chemical and granulometric analyses. Air-dried soil samples were sieved (2.0 mm) and analyzed for total organic matter (OM), remnant phosphorus (Pr) and exchangeable content of Al, K, Ca, Mg, N, P, S, Zn, Cu, Fe and Mn; the sum of bases (SB) is represented as the sum of exchangeable Ca, Mg, and K; the effective cation exchange capacity (CEC) was determined based on SB; the base saturation (V%) was calculated as a percentage SB of the total CEC; and the aluminum saturation (m) was calculated based on effective cation exchange capacity. The pH in H₂O and the potential acidity (H+Al) were also determined. Soil analyses followed the procedures described by EMBRAPA (1997).

Soil water content (SW) was determined using the gravimetric method. The criterion for a dry soil was the soil sample dried to constant weight in an oven at a temperature between 100–110°C (EMBRAPA 1997).

A granulometric analysis was carried out with air-dried soil according to EMBRAPA (1997) to determine the percentages of pebbles (20–200 mm), gravels (2–20 mm) and fine air-dried soil (FADS). The percentage of coarse sand (0.2–2 mm), fine sand (0.05–0.2 mm), silt (0.002–0.05 mm) and clay (<0.002 mm) were determined as a proportion of the fine soil fraction. The cumulative particle-size distribution was plotted in phi (Φ) scale (Folk 1980), using the expression $\Phi_d = -\log_2 d$, where d is the grain diameter in millimeters of the particle corresponding to a given percentile. The central tendency (Mz) and sorting as a dispersion measure (σ_1) were calculated according to Folk and Ward (1957), using the following expressions:

$$M_z = (\Phi_{16} + 50 + \Phi_{84})/3$$

$$\sigma_1 = (\Phi_{84} - \Phi_{16})/4 + (\Phi_{95} - \Phi_5)/6.6$$

The obtained Mz and σ_1 values were classified according to Suguio (1973)

The percentage of the vertical projection area occupied by bare rocks in each plot (BR) was also estimated.

Vegetation Data

The survey was carried out from September 2007 to February 2009 on weekly field trips. All the vascular species were collected, identified and grouped according to the Angiosperm Phylogeny Group (APG 2009). The species cover (%) was estimated as a measure of dominance (Mueller-Dombois and Ellenberg 1974), using the vertical projection of the aerial parts of each species as a percentage of the total area of the plot (Westhoff and van der Maarel 1978). According to Messias et al. (2011) species cover assessment provided a more accurate description of physiognomy of *campos rupestres* than frequency. All the collected specimens were deposited in the Herbarium “Professor José Badini” (OUPR) of the Universidade Federal de Ouro Preto.

Statistical Analyses

Soil variables were tested to check significant differences between the different lithotypes (quartzite and itabirite) and among landforms. These variables were initially submitted to the Kolmogorov-Smirnov test for normality and the Bartlett test for homogeneity of variances (Zar 1996). Because the data did not show normal distribution, even after transformation attempts, they were analyzed with the Kruskal-Wallis and Tukey HSD multiple comparison tests using the software R-package *ggirmess* for ecological data analysis (R Development Core Team 2008).

A canonical correspondence analysis (CCA) was carried out to study the relationships between species dominance and soil variables in the 60 plots (ter Braak 1995). Only 30 of the species with the highest coverage value were included in the first matrix. The soil variables used in CCA were BR, Ca, Cu, FS, Mg, Mn, Mz, S, Sil and σ_1 . Eight soil variables were excluded after a preliminary analysis, due to high collinearity with others. The Monte Carlo test was used to check the significance of eigenvalues and species-soil correlations. Only variables with correlation higher than 0.3 were represented in CCA diagram. The program used was PCOrd (McCune and Mefford 1999).

Results

Soil

In general, the soils were acidic, poor in nutrients and had low values for base saturation, sum of bases and CEC and a great proportion of coarse particles (Table 1). However, the soils in itabirite habitats usually exhibited greater fertility and also a higher level of heavy metals, with higher exchangeable contents of Ca, Cu, Fe, K, Mg, Mn, N and Zn, in addition to higher organic matter content, CEC and lesser aluminum saturation (m) ($P < 0.05$, Table 1). Itabirite pedoenvironments also presented a higher proportion of bare rocks (BR), soil water contents (SW) and a lesser proportion of fine soil (FADS) ($P < 0.05$, Table 1). Nevertheless, the fine soil fraction in itabirite soils showed higher proportions of clay and silt than the quartzite ones. The itabirite soils presented a coarser particle size (smaller Mz values), mainly constituted of gravels and varied from very poorly sorted to extremely poorly sorted. The quartzitic soils, however, varied from poorly to very poorly sorted, mostly consisting of fine sand ($P < 0.05$, Table 1). Only the variables pH, exchangeable content of Al and P were not significantly different among the lithologies. The exchangeable levels of Al, Cu, P, S, Zn, percentage of bare rocks (BR), FADS, peb, SW, pH, m, Pr, CEC and Mz exhibited significant differences among the different geomorphological habitats. Soils in woody savanna habitats presented higher values for CEC and Mz. There was also a high content of OM, N, K, S and Al, as well as a lesser proportion of bare rocks (BR) ($P < 0.05$, Table 1).

Soil-Vegetation Relationships

Altogether 272 species were found, belonging to 70 families, with 168 species found in itabirite (94 species in ISG, 108 in IPG, 137 in IWS) and 175 in quartzitic habitats

Table 1 Soil chemical and physical properties in itabirite and quartzitic rocky outcrops among different habitats. Ouro Preto (20°10' S and 43°31' W) and Mariana (20°13' S and 43°24' W), Brazil. Different letters in the same row indicate statistically significant differences (Mean, n=10, Tukey HSD test, $P<0.05$)

	Unit	Itabirite			Quartzite		
		ISG	IPG	IWS	QSG	QPG	QWS
Al	(cmolc/dm ³)	0.829ab	0.424a	1.022ab	0.819ab	0.435a	1.563b
Ca	(cmolc/dm ³)	0.589a	0.545a	0.567a	0.110b	0.033b	0.074b
Cu	(mg/dm ³)	0.447a	0.321ab	0.356a	0.155bc	0.157bc	0.023c
Fe	(mg/dm ³)	588.96ab	455.10abc	790.69a	155.02c	284.78bc	136.36c
K	(mg/dm ³)	54.3a	61.6a	64.8a	16.2b	11.9b	22.7b
Mg	(cmolc/dm ³)	0.106a	0.112a	0.152a	0.006b	0.005b	0.004b
Mn	(mg/dm ³)	54.62a	49.97a	45.76a	7.95b	2.65b	4.59b
N	(dag/kg)	0.104abc	0.121ab	0.141a	0.04bc	0.019c	0.059abc
P	(mg/dm ³)	2.62 ab	2.36 ab	4.09 a	4.09 a	1.21 b	1.92 b
Pr	(mg/l)	33.60a	33.99a	30.87a	50.31b	49.63b	40.26ab
S	(mg/dm ³)	7.01a	5.85a	8.38a	13.80b	12.46b	17.88c
Zn	(mg/dm ³)	17.345a	13.06ab	8.707bc	4.398c	4.380c	5.449c
m	(%)	37.36a	32.73a	52.71ab	78.75c	76.78bc	90.39c
SB	(cmolc/dm ³)	0.835a	0.813a	0.884a	0.137b	0.159b	0.070b
V	(%)	5.73a	6.38a	5.44a	4.08ab	2.15b	2.56b
pH		5.047ab	5.146ab	4.772a	4.906ab	5.337b	4.859ab
H+Al	(cmolc/dm ³)	14.38a	13.43a	16.46a	6.19b	4.02b	2.34b
CEC	(cmolc/dm ³)	1.539ab	1.343ab	1.906a	0.978ab	0.505b	1.700a
OM	(dag/kg)	11.555a	9.558ab	10.166a	2.623c	1.049c	3.232bc
SW	(%)	1.09ab	0.75ab	2.23b	0.16a	0.42a	0.78ab
peb	(%)	20.6a	8.6bc	9.1ab	0c	0c	0c
gra	(%)	70.5a	61.6a	53.4a	0b	0b	0b
FADS	(%)	8.6a	28.7a	33.4a	100b	100b	100b
CS	(%)	32.9ab	36.2a	29.5ab	27.2ab	22.7ab	19.1b
FS	(%)	28.5a	26.6a	36.1a	57.6b	65.9b	58.5b
sil	(%)	24.3a	25.5a	20.4ab	10.4c	6.9c	13.3bc
cla	(%)	14.3a	11.7a	14.0a	4.8b	4.5b	9.1ab
BR	(%)	88.7a	62.0b	27.5c	83.2a	13.0c	11.2c
Mz		-1.35a	1.65b	3.03bc	4.88 cd	4.73 cd	6.19d
σ_1		5.19a	4.74a	4.96a	1.81b	1.71b	2.70b

ISG – grasslands in sloped areas, with bare itabirite rocks, near the mountain summit; IPG – grasslands on the itabirite plateaus, in the middle of the slope, with no more than a 10 % inclination; IWS – woody savannas in the lower and/or concave parts of the slopes, in valleys or depressions of the itabirite areas; QSG – grasslands in sloped areas, with bare quartzite rocks, near the mountain summit; QPG – grasslands on the quartzite plateaus, in the middle of the slope, with no more than a 10 % inclination; QWS – woody savannas in the lower and concave parts of the slopes, in valleys or depressions of the quartzite area; t – total content; Pr – remnant P; CEC – effective cation exchange capacity; H+Al – exchangeable acidity; m – aluminum saturation; SB – sum of bases; V – base saturation; OM – organic matter; SW – soil water content; peb – pebbles; gra – gravel; FADS – fine air dried soil; CS – coarse sand; FS – fine sand; sil – silt; cla – clay; BR – bare rocks; Mz – granulometry measure, central tendency; σ_1 – granulometry measure, sorting as a dispersion measure.

(93 in QSG, 107 in QPG and 139 in QWS). They belonged mainly to Asteraceae (23.3 %), Poaceae (16.7 %) and Melastomataceae (13.3 %). The sites in the different lithologies were well segregated in CCA (Fig. 1). The eigenvalues of the three first axes of the CCA diagram were significant, the first one explaining 21.3 % of the total variance, the second 8.1 % and the third 5.8 %, totaling 35.2 % of the variance explained (Table 2). The Pearson's correlation index, obtained from the Monte Carlo

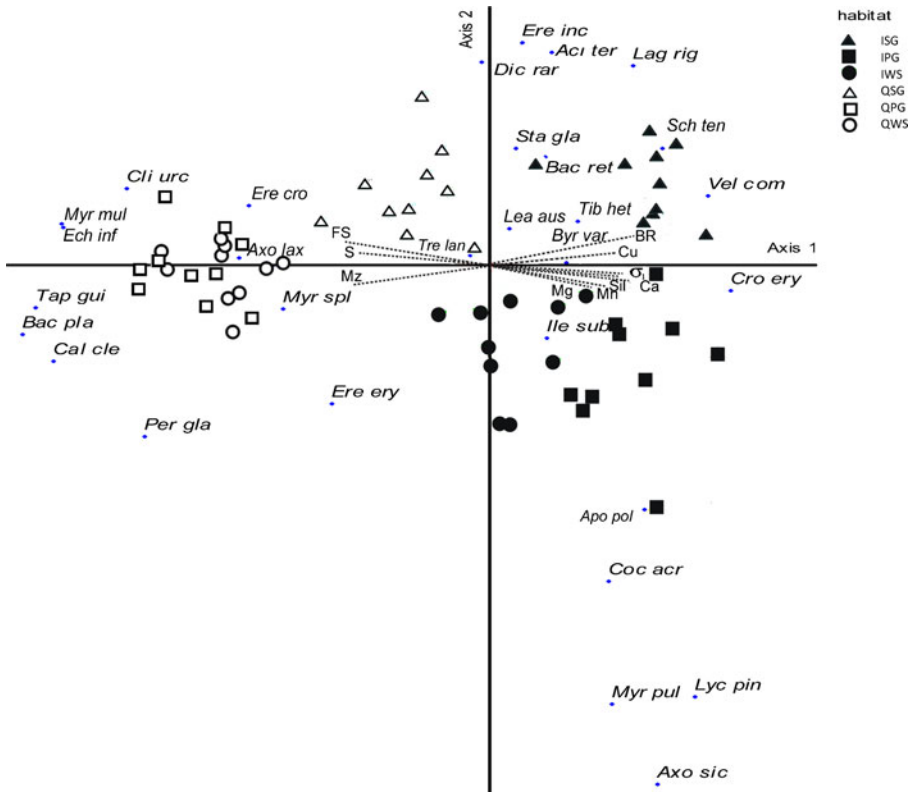


Fig. 1 Ordination diagram of the plots and species obtained by the canonical correspondence analysis, related to data of the 30 highest cover value species and soil variables of 60 plots of rocky outcrops. Soil properties are given as vectors. Plots are designated by symbols representing the different habitats. ISG – grasslands in sloped areas, with bare itabirite rocks, near the mountain summit; IPG – grasslands on the itabirite plateaus, in the middle of the slope, with no more than a 10 % inclination; IWS – woody savannas in the lower and/or concave parts of the slopes, in valleys or depressions of the itabirite areas; QSG – grasslands in sloped areas, with bare quartzite rocks, near the mountain summit; QPG – grasslands on the quartzite plateaus, in the middle of the slope, with no more than a 10 % inclination; QWS – woody savannas in the lower and concave parts of the slopes, in valleys or depressions of the quartzite area; FS – fine sand; sil – silt; BR – bare rocks; Mz – granulometry measure – central tendency; σ_1 – granulometry measure – sorting; Ca – calcium; Cu – copper; Mg – magnesium; Mn – manganese; S – sulphur; *Acı ter* – *Acianthera teres*; *Apo pol* – *Apochloa poliophylla*; *Axo lax* – *Axonopus laxiflorus*; *Axo sic* – *Axonopus siccus*; *Bac pla* – *Baccharis platypoda*; *Bac ret* – *Baccharis reticularia*; *Byr var* – *Byrsonima variabilis*; *Cal cle* – *Calea clematidea*; *Cli urc* – *Clidemia urceolata*; *Coc acr* – *Coccoloba acrostichoides*; *Cro ery* – *Croton erythroxylodes*; *Dic rar* – *Dyckia rariflora*; *Ech inf* – *Echinolaena inflexa*; *Ere cro* – *Eremanthus crotonoides*; *Ere ery* – *Eremanthus erythropapus*; *Ere inc* – *Eremanthus incanus*; *Ile sub* – *Ilex subcordata*; *Lag rig* – *Lagenocarpus rigidus*; *Lea aus* – *Leandra australis*; *Lyc pin* – *Lychnophora pinaster*; *Myr mul* – *Myrcia multiflora*; *Myr pul* – *Myrcia pulchra*; *Myr spl* – *Myrcia splendens*; *Per gla* – *Pera glabrata*; *Sch ten* – *Schizachyrium tenerum*; *Sta gla* – *Stachytarpheta glabra*; *Tap gui* – *Tapirira guianensis*; *Tib het* – *Tibouchina heteromalla*; *Tre lan* – *Trembleya laniflora*; *Vel com* – *Vellozia compacta*

Table 2 Summary of canonical correspondence analysis (CCA) and Monte Carlo permutation test of plant species coverage and soil properties for the studied rocky outcrops

	Axis 1	Axis 2	Axis 3
Eigenvalue	0.650	0.246	0.178
Percentage of variance	21.3	8.1	5.8
Cumulative percentage of variance	21.3	29.4	35.2
Significance of eigenvalues (Monte Carlo test)	0.014	0.021	0.019
Pearson's correlation for species-soil	0.926	0.892	0.861
Significance of correlation (Monte Carlo test)	0.001	0.001	0.001

permutation test (Table 2), showed that species coverage was significantly correlated with soil properties ($r=0.926$, $P<0.001$ in the first axis and $r=0.892$, $P<0.001$ in the second axis).

The first axis was positively correlated to the percentage of bare rocks (BR), σ_1 , silt and the exchangeable contents of Ca, Cu, Mn and Mg; while it was negatively correlated to the Mz, exchangeable content of S and percentage of fine sand (FS) (Fig. 1). This axis separated itabirite from quartzite habitats and also the QSG from the other quartzite habitats. BR and the exchangeable content of Cu were the significant variables positively correlated to the second axis while Mz was negatively correlated. The second axis separated the different habitats in itabirite and also the sloped grasslands with bare rocks in quartzite habitat, from the other habitats in quartzite areas.

The species *Lagenocarpus rigidus*, *Croton erythroxyloides*, *Vellozia compacta*, *Schizachyrium tenerum*, *Acianthera teres*, *Baccharis reticularia*, *Eremanthus incanus*, *Dickya rariflora*, *Stachytarpheta glabra*, *Tibouchina heteromalla* and *Byrsonima variabilis* were associated with habitats having a high percentage of bare rocks, more variation in the soil particle size (σ_1), and a higher content of Ca, Cu, Fe, K, Mn, Mg, N, P and Zn (upper right on Fig. 1). These species had a higher coverage value on ISG, segregating the plots of this habitat. All of these species, except *Croton erythroxyloides*, also occurred in quartzitic areas with bare rocks. *Echinolaena inflexa*, *Clidemia urceolata*, *Eremanthus crotonoides*, *Myrcia multiflora* and *Axonopus laxiflorus*, however, were related to quartzite grassland habitats (left on Fig. 1, near axis 1). The coverage of these species was positively correlated with Mz, contents of fine sand and exchangeable S. The sloped grassland plots (ISG) and the species dominating in this habitat were grouped in the upper right quadrant; the woody savannas (IWS) group of plots (with their dominant species) below the intersection of the two axes and the grassland plateaus with duricrusts (IPG) plots and their typical species (*Coccoloba acrostichoides*, *Myrcia pulchra*, *Lychnophora pinaster* and *Axonopus siccus*) fall into the lower right quadrant. No isolated soil variables were strongly related with the segregation of this last group, but they were slightly conditioned by the content of Mn and Mz. The lower left quadrant displayed species dominating the quartzitic woody savannas. *Myrcia splendens* and *Eremanthus erythropappus* were also in this quadrant between the groups of woody savannas in the different lithologies, occurring in both (Fig. 1). The woody savannas in quartzitic areas were separated mainly by the smaller soil particle size (higher Mz) and the higher proportion of FS (Fig. 1).

Discussion

The soil in the different lithologies and geomorphological habitats presented, as predicted, different chemical and physical properties, which create potential spatial variation on plant species establishment.

The CCA results indicated the existence of a gradient among the habitats (ter Braak 1995). Part of the species distributed more equitably and part were exclusive of particular segments. The high and significant species-environment correlation values in all three axes of CCA show that even though all the sampled soils in *campos rupestres* were poor in nutrients, variations in element contents were enough to determine species composition. Some species were adapted to a soil with more cation content, nutrients or heavy metals, and others seem to dominate environments with very poor soils. In addition, other species were indifferent to variation in soil nutrients being equally distributed along the gradient as *Byrsonima variabilis*, *Ilex subcordata* and *Leandra australis*. In addition, physical properties are also very important in determining the species composition, mainly the occurrence of bare rocks and soil granulometry features.

The first quadrant (upper right on Fig. 1) showed species related to the environment with a higher heavy metal content (Fe, Mn, Zn and Cu) and also some macronutrients (Ca, K, Mg and N), such as *Vellozia compacta*, *Croton erythroxyloides*, *Schizachyrium tenerum*, *Baccharis reticularia* and others. Some species have already been described as a metal-tolerant or hyperaccumulator species and others belong to hyperaccumulator taxa, giving evidence of new species with this feature. Species of *Vellozia* were identified as metal accumulators (Antonovics et al. 1971; Brooks 1998), suggesting adaptations to high metal concentrations in Velloziaceae. Euphorbiaceae was also described as a hyperaccumulator family (Reeves et al. 2007). Asteraceae (*Eremanthus erythropappus* and *E. glomerulatus*) and Melastomataceae (*Microlicia crenulata* and *Trembleya laniflora*), growing on ferruginous soils, presented an accumulation of Cu, Fe, Mn and Zn (Teixeira and Lemos-Filho 1998). Many Myrtales, especially Melastomataceae and Vochysiaceae species were also given as a metal accumulator (Jansen et al. 2002). *Coccoloba acrostichooides* belongs to Caryophyllales, which shows a general ability to accumulate metals in their shoots (Broadley et al. 2001). *Byrsonima variabilis* behaved as an accumulator of Ba, Cu, Mn, Sr and Zn (Correa 2006). These examples and the high metal concentrations in itabirite soils verified in this work and also by Teixeira and Lemos-Filho (1998) and Vincent and Meguro (2008) suggest the occurrence of many metallophytes, or at least metal-tolerant species, in ferruginous rocky outcrops.

The physical properties of soils seem to be very important in determining the vegetation in rocky outcrops. The occurrence of bare rocks influences the distribution of species, separating itabirite from quartzite and also separating the geomorphological habitats, mainly the sloped areas with bare rocks from the others. Conceição and Pirani (2005) and Messias et al. (2011) also found more dominance of Velloziaceae and other phanerophyte species in *campos rupestres* with outcrops whereas in quartzitic plateaus with continuous soils hemicryptophyte species (mainly Poaceae) dominated. Phanerophytic shrubs with sclerophyll leaves, common in areas with outcrops can extract water from dry soils at low water potential and are typically long-lived. Their photosynthetic capacity is low because of internal shading within the leaves and/or high

mesophyll resistance to CO₂ diffusion (Lloyd et al. 1992). So, sclerophylls can dominate in some dry environments, such as the sloped grasslands with outcrops, but do not compete effectively in quartzitic plateaus where seasonal flooding occurs. Giuletta et al. (1997) and Jacobi et al. (2007) also pointed out that the microhabitats created by the outcrops or the existence of vertical fissures on the rocks allow the rooting of taller species like phanerophytes. In addition, shrubby erect species of Velloziaceae, like *Vellozia compacta*, seemingly cannot dwell in deeper and mechanically unstable sandy soils found in the quartzitic plateaus (Alves and Kolbek 2010). The central tendency measure (Mz) and the variation of soil particle size (σ_1) are important factors determining physical soil properties like penetrability of roots, water retention capacity, and permeability, as well as other chemical properties like CEC and nutrient availability (Hazelton and Murphy 2007). However, the poor drainage observed in the QPG may not be related to these variables, but is probably due to the topography, restricting the rainfall runoff and by the continuous and impermeable quartzite bedrock under the shallow soil, hindering vertical percolation. The high coverage of hemicryptophytes in QPG may be related to the adaptation of the grasses to the seasonal flooding (Visser et al. 2000; Mollard et al. 2008) and the ability of hemicryptophytes to explore the upper layer of the soil, which is richer in nutrients (Dutra 2005). In addition, the species with a high coverage in QPG (*Echinolaena inflexa*, *Eremanthus crotonoides* and *Clidemia urceolata*) seemed to be well adapted to very low nutrient contents but not to tolerating high levels of heavy metals.

Some soil variables, mainly the physical ones, explained the segregation of grasslands from woody savannas. The woody savannas are determined by areas with smaller particle size, a lesser bare rock proportion, a higher CEC, contents of organic matter and *Al. Tapirira guianensis*, *Baccharis platypoda*, *Calea clematidea* and *Pera glabrata* are phanerophyte species, commonly found in QWS. They need a thicker soil to grow, which was found in the colluvial soil present in the depressions or concave parts of the slopes. Even though it was not measured, convergent hollows usually accumulate sediment from surrounding ridges or side slopes, in addition to the in-situ disintegration of the bedrock (Matsushi et al. 2006). The higher Mz in QWS suggests the downward transportation in larger proportions of smaller soil particles from higher parts of the slopes. These species were also related to the content of exchangeable S, which was higher in quartzite woody savannas due to the richness in organic matter. As stated by Camargo and Sparovek (1997), the vegetation itself influences soil characteristics at the upper layers and vice-versa; for instance, by transferring organic matter through nutrient cycling. Suitable physical or nutritional conditions afford greater productivity, generating a higher amount of organic matter, giving rise to a feedback loop. Thus, the higher content of exchangeable Al in the woody savanna habitats would be explained by the thicker soils, allowing the dwelling of taller species and by the occurrence of many species able to accumulate aluminum in their leaves (Haridasan 1982), which transfer this element to the soil through litter deposition and decomposition. According to Jansen et al. (2002) many species of Myrtales are Al accumulators, especially Melastomataceae, Vochysiaceae and Myrtaceae, very common families in this survey and *campos rupestres* habitats in general (Meguro et al. 1994; Giuletta et al. 1997; Mourão and Stehmann 2007). According to Haridasan (1982), aluminum-accumulating species of these families, in Brazilian savannas, seem to have an efficient mechanism for absorbing all cations from the soil.

The grasslands on the plateaus (QPG) and woody savannas (QWS) in quartzite were not so well discriminated. It suggests that other variables, besides those measured in this study, such as the duration of the saturation and soil thickness should have been evaluated. In addition, none of the measured soil variables alone explained the segregation of the most abundant species in the ferruginous plateaus (*Lychnophora pinaster*, *Myrcia pulchra*, *Axonopus siccus*, *Coccoloba acrostichoides* and *Apochloa poliophylla*). Even though not statistically significant, the soil of the ferruginous plateaus (IPG) showed the lowest proportion of fine sand and clay, lower metal contents than in ISG, the highest proportions of coarse sand and silt, and a slightly higher value of pH, which may be the cause of the segregation of these species (in the lower right quadrant). Moreover, this habitat has a harder substrate, which raises difficulties for root penetration. Some other factors besides those measured in this work, or several factors acting together (instead of a single strong factor), may be influencing the screening of the species in this environment. But, in contrast with the others of the upper right quadrant, these species did not present any significant correlation with the contents of macronutrients, except N and only some correlation with Mn, Cu and Zn. In fact, Oliveira Junior et al. (2006) related that *Lychnophora pinaster* is an aluminum-tolerant species, not exigent in macronutrients, but needs considerable contents of Mn and Zn, which corroborate its adaptability to poor soils containing a high level of metals.

Vegetation composition in rocky outcrops was influenced by the geochemistry, geomorphology and physical properties of the soils. Even though the soil itself was not enough to explain all the differences found in the vegetation, it explained much of the variation observed in the flora. The individual role of each soil variable and its correlation with each species is less important than the analysis of the soil as a complex environment. None of the variables plays just one function in the soil, but all of them interact among themselves constituting a complex pedoenvironment, influencing the vegetation.

Even though such ferruginous areas would be grouped with the most common quartzite-sandstone areas under the name “*campos rupestres*”, they are actually particular and harbor many metallophyte species. There are only two parks harboring ferruginous rocky outcrops in the Quadrilátero Ferrífero and mining activities have caused great destruction to this still poorly known and very rich ecosystem. So, special attention must be given to its preservation by improving mining regulatory measures and creating new conservation areas.

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