Floresta e Ambiente 2019; 26(2): e20171039
https://doi.org/10.1590/2179-8087.103917
ISSN 2179-8087 (online)

Original Article

Conservação da Natureza

Edaphic Filters and Plant Colonization in a Mine Revegetated with Sewage Sludge

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ABSTRACT

We evaluated the recruitment of plant species and their relation with edaphic attributes in a mine revegetated with sewage sludge in the Brazilian Federal District. Plant species in the revegetated mine and in remaining portions of Cerrado (savanna) within the mined landscape were sampled and identified. Then, samples of revegetated substrate and soils from Cerrado portions were collected, analyzed for chemical attributes and submitted to statistical tests. Results indicated that the remaining portions of Cerrado were colonized by 91 species (22% allochthonous species), and the revegetated substrate housed 62 species (55% allochthonous species). Multivariate tests showed that the edaphic condition built from the incorporation of sewage sludge into the mining substrate acted as filter on the assemblage of plant species. Despite the two study sites shared the same landscape, the Cerrado portions and the revegetated substrate did not share similar plant communities after a decade from mine rehabilitation works.

Keywords: plant recruitment, ecological restoration, biosolids, Cerrado.

1. INTRODUCTION

Surface mining is one of the most severe forms of environmental degradation and anthropogenic alteration of habitats (Wijesekara et al., 2016). Vegetation removal and soil excavation for reaching minerals drastically reduce ecosystem resilience and its functions (Domene et al., 2010; Corrêa et al., 2017). Surface mining in the Brazilian Federal District (BFD) is based on low investments in operations, small mining extensions, and poor control over mineral exploration, impact mitigation, and ecological restoration (Corrêa et al., 2004).

Substrates exposed to the surface by mining present inappropriate conditions for the establishment of plants and other organisms (Goedert & Corrêa, 2004; Corrêa & Bento, 2010), and the incorporation of high rates of organic matter into substrates (> 50 Mg. ha^{-1} dry basis) has been the solution to build a suitable edaphic environment on mined sites. Thus, the rehabilitation of exploited mines involves physical, chemical, and biological amendments of exposed substrates that along with propagules of regional species should trigger the autogenic succession in the revegetated sites (Corrêa et al., 2007).

Due to economic reasons and to stimulate recycling, urban residues, such as sewage sludge, have been applied to exploited mines as source of organic matter and plant nutrients since 1994 in the BFD (Corrêa, 2009). Sanitary issues that limit the use of sewage sludge in agriculture are not impediments for using it in mines (Corrêa, 2009). Increase of organic matter content, nutrient concentrations, and microbial biomass (Domene et al., 2010; Gardner et al., 2010; Torri et al., 2014; Wijesekara et al., 2016), improvement of physical attributes (De Maria et al., 2007; Jordán et al., 2017), and spontaneous revegetation of surfaces (Andrés et al., 2007; Borges et al., 2009; Silva et al. 2013) follow the incorporation of organic residues into mining substrates.

The processes that classify and restrict species establishment on a site during the course of ecological restoration are designated as ecological filters (Hulvey & Aigner, 2014). The literature commonly identifies three major ecological filters: 1) limitations on seed dispersion or seed rain that prevent species to reach the restoration site (Funk et al., 2008; Oster et al., 2009); 2) abiotic local conditions that favor or difficult the establishment and survival of some group of species (Cleland et al., 2013; Sollenberger et al., 2016); 3) biotic interactions between species that limit (competition) or facilitate (facilitation) the establishment, persistence and abundance of some species on a site (Funk et al., 2008; Cleland et al., 2013).

Although some studies have offered an expressive contribution to the advance of knowledge on the rehabilitation of areas degraded by the mining (Corrêa et al., 2007; Corrêa, 2009; Daws et al., 2013; Nussbaumer et al., 2016; Wijesekara et al., 2016), few studies have investigated the role of edaphic filters in plant recruitment on sites revegetated with sewage sludge (Corrêa et al., 2017). Therefore, this study aimed to investigate the relation between edaphic filters and plant colonization in a gravel mine revegetated with sewage sludge, having remaining portions of the original soil and native vegetation within the mined landscape as references.

2. MATERIAL AND METHODS

The area of this study was located on the margin of the highway BR-060 (15°57’6.45” S, 48°10’40.42” W, Datum WGS 84) in the southwestern portion of the Brazilian Federal District (BFD), which extends for 5,814 km^2 on the Brazilian Central Plateau. Regional topography varies from flat to gently sloped, with average altitude of 1,100 m. Climate is Tropical of Savanna (Aw – Köppen Geiger) with well-defined wet and dry seasons. Annual mean temperature ranges from 21 °C to 24 °C and annual rainfall ranges from 1,200 to 1,600 mm, with 95% of precipitation occurring between September and March.

Lateritic gravel was explored from the study site in 2001 and 2002, and mine operations left a 67 ha crater from 4 to 5 m bellow the original ground level (Figure 1). The original soil on the area was a Haplic Inceptisol – Cambissolo (EMBRAPA, 2013), which supported Cerrado *sensu stricto* vegetation type. Rehabilitation works involved the incorporation of 130 Mg ha^{-1} (dry basis) of domestic sewage sludge into the exposed substrate surface (0-15 cm) in 2002. *Urochloa brizantha* (7 kg ha^{-1}) was sown on the rehabilitated substrate in 2005, and since then the area has been used as pasture for approximately thirty bovines. Remaining portions of the original soil and Cerrado vegetation (mounds)

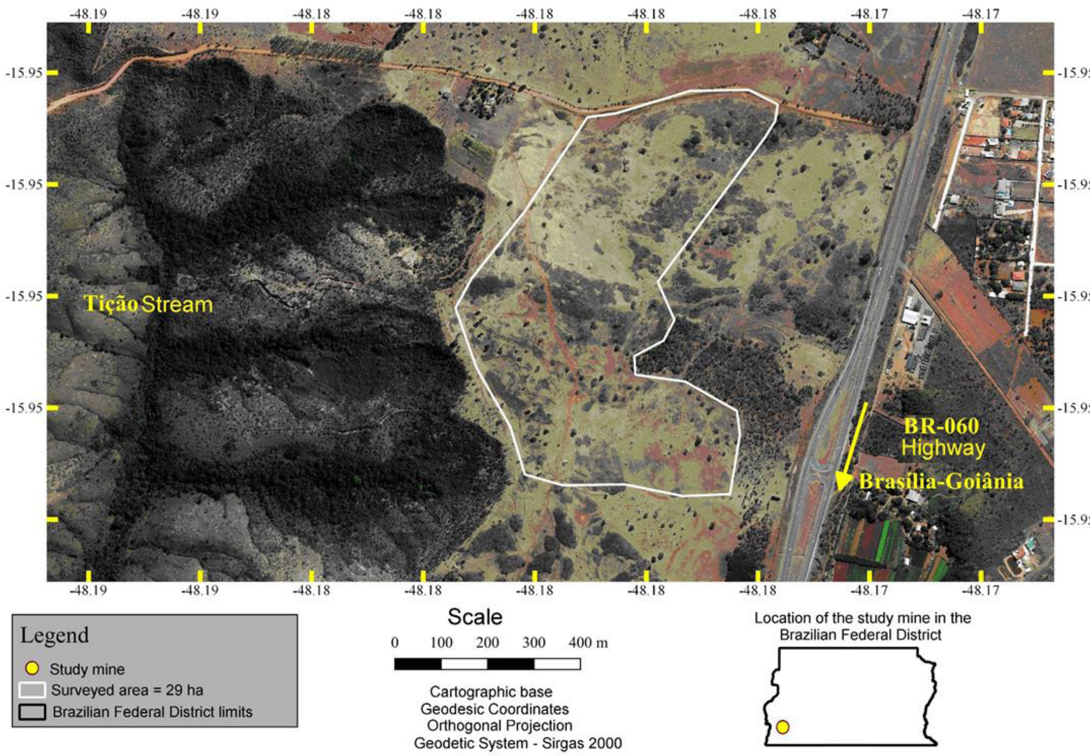

Figure 1. Location of the sampled 29 ha within the 67 ha mined site. Data source: Codeplan (2017).

were left in the midst of the mined landscape, just 4 - 5 m above mined surface. The Cerrado vegetation on mounds continued to produce seeds and propagules dispersed to the neighborhood.

A floristic survey of species naturally recruited in the rehabilitated mine substrate and in the remaining portions of Cerrado (mounds) was done ten years after sewage sludge incorporation into the exposed mine surface. Stratified sampling was chosen for the floristic survey due to the presence of two biotopes within the same site. Remaining portions of Cerrado (mounds) were selected at random and circular areas of 15 m radius were delimited around them on the rehabilitated mine surface (Figure 2). Rarefaction curves periodically tested the sampling sufficiency for each of the two biotopes until curves tended to stabilization, which was reached after sampling 15 mounds and respective areas on the rehabilitated substrate around them – 15 sampling units (Figure 3). The extension effectively sampled was 1.88 ha, of which 0.12 ha on mounds and 1.76 ha on the rehabilitated mine surface. All recruited plant species were recorded and three composite samples of soil and substrate (five subsamples – 0 to 15 cm depth) were collected from each sampling unit. Plant species not identified on the spot were photographed and collected for further identification in herbarium.

Names of sampled plant species were updated (Species Link, 2017), and species were classified according to life form (grass, bindweed grass, subshrub, shrub, or tree), origin (autochthonous or alochthonous to Cerrado formations), and invasion capacity of natural environments, rural areas, and pastures (Lorenzi, 2008; Mendonça et al., 2008).

Soil and substrate samples were air-dried, sieved (2 mm), and analyzed for organic matter (OM), total nitrogen (total-N), available phosphorus (available-P), exchangeable potassium (exchangeable-K), calcium (Ca^{2+}), magnesium (Mg^{2+}), active acidity (pH), potential acidity ($H^{+} + Al^{3+}$), cationic exchange capacity (CEC), and base saturation (V%). The analysis of organic matter (OM) followed the method of humid combustion (Walkley-Black) and posterior titration with an ammoniac ferrous sulphate solution. Total nitrogen was analyzed by the Kjeldahl method. Available-P and

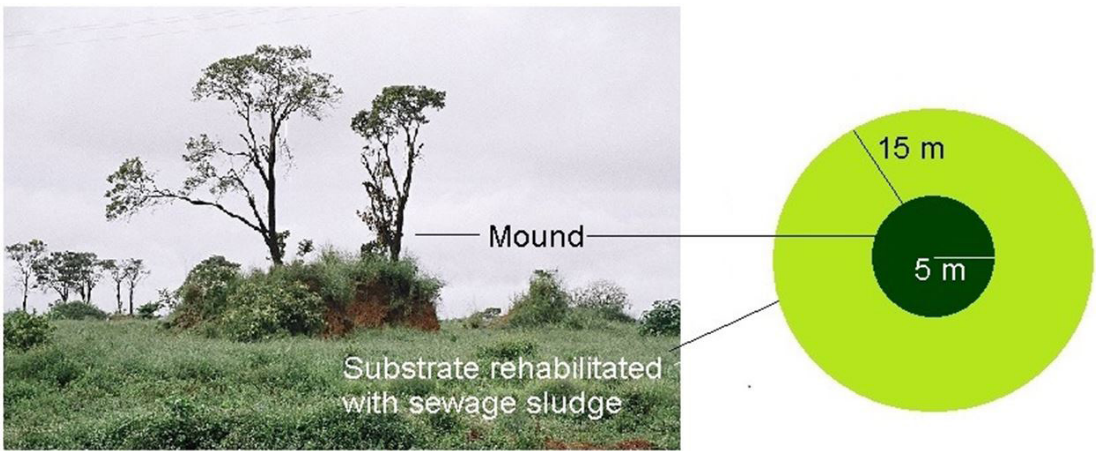

Figure 2. Sampling unit designed according to mound locations (D1 to D15) and surround areas. The dark green circle regards to the area on mounds and the light green circle to the area on the revegetated substrate around mounds.

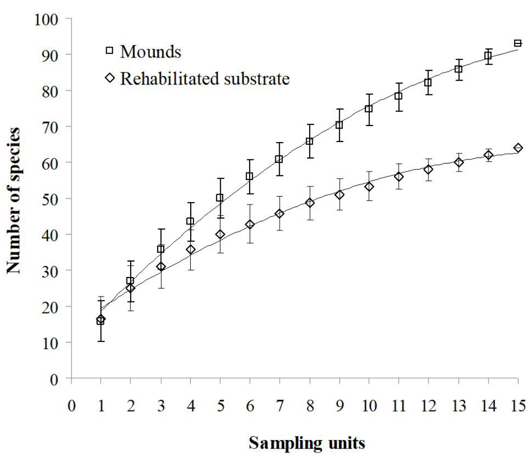

Figure 3. Rarefaction curves of plant species sampled on mounds and on the substrate rehabilitated with sewage sludge.

exchangeable-K were extracted with Mehlich-1 solution and concentrations were respectively determined in a photocolorimeter and spectrophotometer of atomic absorption. Ca^{2+} and Mg^{2+} were extracted with KCl solution and analyzed by spectrophotometer of atomic absorption. Soil and substrate samples were shaken with 0.01 M $CaCl_2$ solution and analyzed for active acidity in a pH meter. Potential acidity was determined by means of a buffered solution of calcium acetate and subsequent titration with NaOH. From the obtained results, CEC and V% were calculated according to Embrapa (1997).

Results were submitted to analysis of variance, test of Student, and Mood Median test in Minitab 15 software. The influence of the edaphic attributes on the distribution of recruited plant species was investigated by using the Canonical Correspondence Analysis (CCA). The CCA examines responses of species and sampling units to environmental variables. Thus, unlike other ordination techniques, the CCA provides a direct analysis of gradients (Ter Braak, 1987). To meet CCA prerequisites, data were organized into two matrices and processed in R 3.3.1 version software (R Core Team, 2016). Plant species matrix contained categorical values (presence = 1 and absence = 0). We used only the species that occurred in at least two of the 15 sampled units and eliminated accidental species from the CCA (Dajoz, 2005). This procedure is recommended in ordination techniques, because accidental species do not significantly affect results but increase the volume of calculations and errors (Gauch, 1982). The metric values of the edaphic attributes constituted the second matrix. To test the probability of relation between the matrices of plant species and edaphic attributes, we used the Monte Carlo permutation test (Ter Braak & Prentice, 1988). Flora similarity between mounds and rehabilitated substrate was evaluated by Anosim test, and the correlation between ordinations of sampling units depending on species composition and edaphic conditions was analyzed by Procrustes test.

3. RESULTS

Rarefaction curves indicated that the sampling of 15 remaining portions of Cerrado (mounds) and the respective surroundings was enough to represent the flora of the study area (Figure 3). It was found 131 plant species colonizing the soil on mounds and the rehabilitated substrate ten years after the incorporation of sewage sludge into the exposed mined surface. Out the 131 plant species, 91 appeared on mounds, of which 76% were unique to this biotope, 22% allochthonous, 38% invasive, 45% trees, 18% shrubs, and 40% herbs/subshrubs. Sixty two species recruited on the rehabilitated substrate, of which 65% were unique to this other biotope, being 55% allochthonous, 83% invasive, 14% trees, 16% shrubs, and 73% herbs/subshrubs (Table 1).

Sewage sludge applied at 130 Mg ha^{-1} (dry basis) to the exposed substrate resulted in high fertility levels in relation to the values found in soils on mounds (Table 2). The concentration of available-P in the rehabilitated substrate, for instance, reached 46 times the value found in the original Cerrado soil (Table 2). The other edaphic attributes also presented significantly different values in the two biotopes, except potential acidity ($H^+ + Al^{3+}$) (Table 2).

Eigenvalues for axes 1 and 2 from the Canonical Correspondence Analysis (CCA) were 0.19 and 0.54, respectively. Axis 1 explained 16.2% of the variance and axis 2, 5.9% of the same. The low 22.1% variance is common in ecological data ordinations due to the complexity of factors involved in the determination of communities' floristic compositions (Ter Braak & Prentice, 1988). Monte Carlo permutation test was

Table 1. Sampled plant species in the study area.

Species	Life form	Origin	Invasive?	Location
Acanthospermum australe (Loefl.) Kuntze	herb	allochthonous	yes	D
Achyrocline satureoides (Lam.) DC.	herb	autochthonous	yes	S
Acosmium dasycarpum (Vogel) Yakovl	tree	autochthonous	no	D
Aegiphila lhotzkiana Cham.	tree	autochthonous	no	D
Ageratum conyzoides L.	herb	allochthonous	yes	D/S
Alibertia cf *sessilis* (Vell.) K. Schum.	tree	autochthonous	no	D
Amaranthus sp	herb	-	-	S
Annona crassiflora Mart.	tree	autochthonous	no	D
Annona tomentosa R.E.Fr.	shrub	autochthonous	no	D
Asclepias cf *curassavica* L.	herb	allochthonous	yes	D/S
Aspidosperma tomentosum Mart.	tree	autochthonous	no	D
Asteraceae sp1	herb	-	-	S
Asteraceae sp2	herb	-	-	D
Axonopus capillaris (Lam.) Chase	herb	autochthonous	no	D
Bauhinia sp	shrub	-	-	D
Borreria latifolia (Aubl.) K. Schum.	herb	autochthonous	sim	D
Byrsonima coccolobifolia Kunth	tree	autochthonous	no	D
Byrsonima sp1	-	-	-	D
Casearia silvestris Sw.	tree	autochthonous	no	D
Cecropia cf *pachystachya* Miq.	tree	autochthonous	yes	S
Chamaecrista rotundifolia (Pers.) Greene	herb	allochthonous	yes	D
Cissampelos sp	climbing herb	-	-	D
Cleome spinosa Jacq.	sub-shrub	allochthonous	yes	S
Commelinaceae sp	climbing herb	-	-	S
Connarus suberosus Planch.	tree	autochthonous	yes	D
Copaifera langsdorffii Desf.	tree	autochthonous	no	D
Cucurbitaceae sp	climbing herb	-	-	S

D = mounds; S = substrate rehabilitated with sewage sludge.

Table 1. Continued...

Species	Life form	Origin	Invasive?	Location
Cyperus surinamensis Rottb.	herb	autochthonous	yes	S
Cyperus cf *odoratus* L.	herb	allochthonous	yes	S
Dalbergia miscolobium Benth.	tree	autochthonous	no	D
Davilla elliptica A.St.-Hil.	tree	autochthonous	no	D/S
Digitaria insularis (L.) Fedde	herb	allochthonous	yes	S
Dimorphandra mollis Benth.	tree	autochthonous	yes	S
Diospyros burchellii Hiern	tree	autochthonous	no	D
Emilia fosbergii Nicolson	herb	allochthonous	yes	D/S
Eriotheca pubescens (Mart. & Zucc.) Schott & Endl.	tree	autochthonous	no	D
Erythroxylum deciduum A. St.-Hil	tree	autochthonous	no	D
Erythroxylum sp	tree	-	-	D
Erythroxylum tortuosum Mart.	tree	autochthonous	no	D
Eugenia dysenterica DC.	tree	autochthonous	no	D
Fabaceae sp	-	-	-	D
Handroanthus ochraceus (Cham.) Mattos	tree	autochthonous	no	D
Hortia brasiliana Vand. ex DC.	shrub	autochthonous	no	D
Hymenaea stigonocarpa Mart. ex Hayne	tree	autochthonous	no	D
Hyptis suaveolens (L.) Poit.	sub-shrub	allochthonous	yes	D/S
Ipomoea nil (L.) Roth	climbing herb	allochthonous	yes	S
Ipomoea triloba L.	climbing herb	allochthonous	yes	S
Jacaranda ulei Bureau & K.Schum.	shrub	autochthonous	no	D
Lamiaceae sp1	herb	-	-	D/S
Lantana camara L.	sub-shrub	allochthonous	yes	D
Leonotis nepetifolia (L.) R. Br.	herb	allochthonous	yes	S
Lepidaploa aurea (Mart. ex DC.) H.Rob.	shrub	autochthonous	no	D/S
Lippia cf *alba* (Mill.) N.E. Br. ex Britton & P. Wilson	sub-shrub	allochthonous	yes	D
Ludwigia cf *tomentosa* (Cambess.) H. Hara	sub-shrub	autochthonous	yes	S
Malvastrum coromandelianum (L.) Garcke	sub-shrub	allochthonous	yes	S
Maprounea guianensis Aubl.	tree	autochthonous	no	D
Melia azedarach L.	tree	allochthonous	no	S
Miconia stenostachya DC.	tree	autochthonous	no	S
Mimosa caesalpiniifolia Benth.	tree	autochthonous	no	S
Mimosa pigra L.	shrub	allochthonous	yes	D/S
Myrtaceae sp1	-	-	-	D
Myrtaceae sp2	-	-	-	D
Myrtaceae sp3	-	-	-	D
Não identificadas	-	-	-	D/S
Nicotiana tabacum L.	herb	allochthonous	no	S
Ouratea floribunda Engl.	shrub	autochthonous	no	D
Pavonia sp	sub-shrub	-	-	D
Pennisetum setosum (Sw.) Rich.	herb	allochthonous	yes	S
Piper aduncum L.	shrub	autochthonous	yes	S
Plathymenia reticulata Benth.	tree	autochthonous	no	D
Poaceae sp1	herb	-	-	S
Poaceae sp2	herb	-	-	D
Poaceae sp3	herb	-	-	S
Psidium myrsinoides O. Berg	tree	autochthonous	no	D

D = mounds; S = substrate rehabilitated with sewage sludge.

Table 1. Continued...

Species	Life form	Origin	Invasive?	Location
Psidium pohlianum O. Berg	tree	autochthonous	no	D
Qualea grandiflora Mart.	tree	autochthonous	no	D
Ricardia sp	-	-	-	D
Ricinus communis L.	shrub	allochthonous	yes	S
Roupala montana Aubl.	tree	autochthonous	no	D
Rubiaceae sp	-	-	-	D/S
Scoparia dulcis L.	herb	allochthonous	yes	S
Senna obtusifolia (L.) H.S. Irwin & Barneby	sub-shrub	allochthonous	yes	D/S
Senna occidentalis (L.) Link	herb	allochthonous	yes	S
Sida glaziovii K. Schum.	sub-shrub	autochthonous	yes	D/S
Sida rhombifolia L.	sub-shrub	allochthonous	yes	D/S
Sidastrum micranthum (A. St.-Hil.) Fryxell	herb	autochthonous	yes	D/S
Simarouba cf *versicolor* A. St.-Hil.	tree	autochthonous	no	D
Smilax goyazana A. DC.	climbing herb	autochthonous	no	D
Solanum americanum Mill.	shrub	allochthonous	yes	D/S
Solanum falciforme Farruggia.	tree	autochthonous	yes	D/S
Solanum palinacanthum Dunal.	shrub	autochthonous	yes	D/S
Solanum sp1	-	-	-	D
Solanum sp2	-	-	-	S
Solanum subumbellatum Vell.	shrub	autochthonous	no	D
Stachytarpheta elatior Schrad. ex Schult.	sub-shrub	autochthonous	yes	S
Stylosanthes guianensis (Aubl.) Sw.	herb	autochthonous	yes	D/S
Stylosanthes sp	herb	-	-	D
Tabebuia roseoalba (Ridley) Sandw.	tree	autochthonous	no	D
Tachigali vulgaris L.G.Silva & H.C.Lima.	tree	autochthonous	no	D
Tagetes minuta L.	herb	allochthonous	yes	D/S
Triumfetta rhomboidea Jacq.	sub-shrub	allochthonous	yes	S
Urochloa plantaginea (Link) Hitchc.	herb	allochthonous	yes	D/S
Verbenaceae sp	-	-	-	S
Vernonanthura ferruginea (Less.) H. Rob.	shrub	autochthonous	yes	D/S
Vernonia polyanthes Less.	shrub	autochthonous	yes	S
Vernonia rubriramea Mart. ex DC.	shrub	autochthonous	no	D
Vernonia sp1	herb	-	-	D/S
Vernonia sp2	herb	-	-	S
Waltheria cf *indica* L.	herb	allochthonous	yes	D
Xylopia aromatica (Lam.) Mart.	tree	autochthonous	no	D
Zanthoxylum rhoifolium Lam.	tree	autochthonous	no	D
Zornia curvata Mohlenbr.	herb	autochthonous	no	S

D = mounds; S = substrate rehabilitated with sewage sludge.

significant for CCA ($p = 0.001$) and for axes 1 and 2 ($p = 0.001$ and 0.022, respectively). The CCA ordination diagrams (Figure 4) and ANOSIM groups test ($p = 0.001$) showed that the analyzed edaphic attributes were significantly different between the soil on mounds and the substrate rehabilitated with sewage sludge (Table 2). Likewise, the flora from these two biotopes was also significantly different. Procrustes test ($p = 0.001$) showed high correlation between the edaphic variables and the floristic compositions in the two study biotopes ($r = 0.86$).

The ordination diagram of species as a function of edaphic conditions (Figure 4) formed two distinct floristic groups: the first group associated with low edaphic fertility was composed of *Acanthospermum australe*, *Aegiphila lhotzkiana*, *Annona tomentosa*, *Borreria latifolia*, *Byrsonima*

Table 2. Edaphic attributes of soil on mounds (D) and of rehabilitated substrate (S).

Attribute	Sample	OM	N	P	K	Ca	Mg	H+Al	CEC	V%	pH
Mean	D	5.59a	2.16a	0.02a	0.12a	1.05a	0.51a	9.83a	11.51a	14.93a	4.09a
	S	7.94b	3.97b	0.91b	0.28b	4.44b	1.39b	9.02a	15.75b	42.53b	4.85b
Median	D	5.31a	2.20a	0.02a	0.12a	0.95a	0.43a	9.74a	11.63a	13.00a	4.10a
	S	8.25b	3.85b	0.88b	0.24b	4.30b	1.33b	9.44a	15.98b	42.27b	4.80b

OM = organic matter (dag.kg^{-1}); N = total nitrogen (g.kg^{-1}); P = available phosphorus (g.kg^{-1}); K = exchangeable potassium (cmolc.kg^{-1}); Ca = calcium (cmolc.kg^{-1}); Mg = magnesium (cmolc.Kg^{-1}); $H^+ + Al^{3+}$ = potential acidity (cmolc.kg^{-1}); CEC = cation exchange capacity (cmolc.Kg^{-1}); V% = base saturation (%); and pH = active acidity; Means and medians for each attribute followed by the same letter do not statistically differ by Student's and Mood Median tests ($p < 0.05$), respectively.

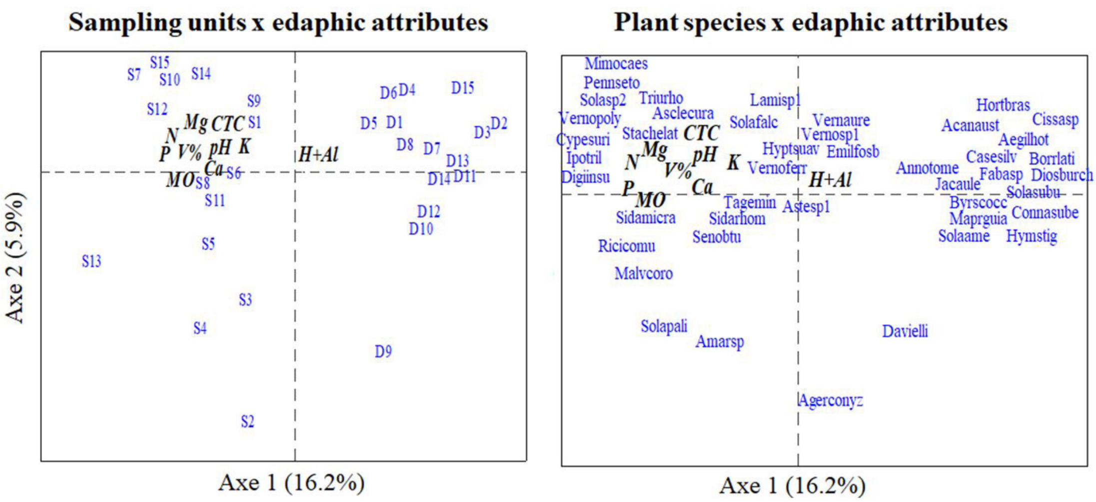

Figure 4. Canonical Correspondence Analysis (CCA) ordination for distribution of sampling units (mounds = D1 to D15; and rehabilitated substrate = S1 to S15) according to edaphic attributes (Table 2), and distribution of species (Table 1) influenced by edaphic attributes (Table 2). The first four letters of the generic and specific epithets abbreviated the scientific names of species.

coccolobifolia, *Casearia Sylvestris*, *Connarus suberosus*, *Davilla elliptica*, *Diospyros burchellii*, *Hortia brasiliana*, *Hymenaea stigonocarpa*, *Jacaranda ulei*, and *Maprounea guianensis* (Table 1). In this first group, 93% of species appeared exclusively on mounds and are autochthonous to Cerrado. The second group of plant species correlated with the fertility conditions present in the rehabilitated substrate (Table 2) and was composed of *Asclepias curassavica*, *Cyperus surinamensis*, *Digitaria insularis*, *Ipomoea triloba*, *Malvastrum coromandelianum*, *Pennisetum setosum*, *Ricinus comunins*, *Senna obtusifolia*, *Sida rhombifolia*, *Sidastrum micranthum*, *Solanum falciforme*, *Solanum palinacanthum*, *Stachytarpheta elatior*, *Tagetes minuta*, *Triumfetta rhomboidea*, *Vernonanthura ferruginea*, and *Vernonia polyanthes*. In this last group, 59% of species are allochthonous and invasive of savannic formations of Cerrado.

4. DISCUSSION

The Cerrado biome has different expressions of vegetation climax such as grasslands, savannas, and forests (Eiten, 1972). These vegetation physiognomies grow under the same climate and are molded by particular soil conditions (Ratter et al., 2003; Moreno et al., 2008; Neri et al., 2012; Schaefer et al., 2015). Effective soil depth, course material along the soil profile, depth of the groundwater table, soil drainage degree, and soil fertility level define different Cerrado phytophysiognomies, vegetation expressions of the edaphic climax in the biome (Haridasan, 2008).

In addition to these variations, floristic composition, phytosociology, and productivity can differ within the same physiognomy due to variations in soil fertility and physical characteristics (Haridasan, 2008). Despite the edaphic climax that rules the Cerrado flora, studies on the influence of edaphic conditions on plant colonization in mining sites are rather scarce (Starr et al., 2013).

Plant colonization starts with propagules entering a disturbed area, and these species must pass through abiotic filters prior to establishing an initial community in it (Hobbs & Norton, 2004). The successful seedlings will be further submitted to biotic filters such as competition, facilitation, predation, and parasitism. In this sense, the intensity of each filter type will influence the level of environmental stress imposed on recovering communities during ecological succession (Hobbs & Norton, 2004). Some studies suggest that edaphic limitations of exposed substrates and dominance of invasive grasses (Poaceae) are the major ecological filters restricting the establishment and growth of autochthonous species in areas degraded by mining activities (Goedert & Corrêa, 2004; Martins et al., 2004; Halassy et al., 2016; Sollenberger et al., 2016).

In this study, portions of Cerrado vegetation remained on mounds and acted as sources of propagules within the mined landscape (Figure 2). Even though, only 17% of the total sampled species (22 species) were common to the floristic communities on the mounds and on the rehabilitated substrate. Of these 22 species, 8 (44%) were classified as autochthonous, and 10 (56%) were classified as allochthonous and invasive of savanna formations of Cerrado (Table 1). In addition to the edaphic characteristics of each sampled biotope (Table 2), roots and underground stems that remain buried in substrates after mine exploitation (Corrêa et al., 1998) and low production and longevity of seeds from some Cerrado woody species (Salazar et al., 2012) may have influenced the low floristic similarity between the two plant communities within the same mined landscape. Long-term ecological studies indicate that the similarity between plant communities of a natural area of Cerrado and other area regenerated from deforestation is higher than the similarity between the same natural area and other area regenerated from mining activity (Corrêa & Leite, 1998; Corrêa, 2009). Even in the absence of physical barriers, as it is the case of this study, species that inhabit closely neighboring locations can be allopatric (excluding) if soil conditions define different biotopes (Dajoz, 2005).

The number of plant species sampled on mounds (91) and on the rehabilitated substrate (62) (Table 1) was below the floristic richness found in savannic formations of Cerrado (Felfili et al., 2001; Munhoz & Felfili, 2006). However, the number of woody species sampled in the mine rehabilitated with sewage sludge (Table 1) was within the range registered for mines abandoned to natural regeneration in the Brazilian Federal District (Corrêa et al., 2007). Allochthonous and invasive species of savanna and grassland formations of Cerrado were found both on the mounds under Cerrado vegetation cover and on the rehabilitated substrate (Table 1). Allochthonous species can become invasive and cause negative impacts to invaded environments (Sampaio & Schmidt, 2013) due to their higher ability to compete and dominate plant communities relative to autochthonous species (Valéry et al. 2008).

Sewage sludge applied to the mined surface at 130 Mg ha^{-1} increased substrate fertility to levels far above those measured in the soil under the natural vegetation cover (Table 2) and in Cerrado soils under agricultural production (Correia et al., 2004). The rehabilitated substrate was dominated by grass species (Poaceae) and, even in areas under savanna vegetation cover, additions of phosphorus and nitrogen have favored the dominance of invasive grasses to the detriment of autochthonous species (Bustamante et al., 2012; Lannes et al., 2015). Studies on plant nutrition have shown that the majority of autochthonous species of Cerrado are resistant or tolerant to the dystrophy condition of Cerrado soils (Haridasan, 2008), and that high levels of soil fertility favor the establishment of allochthonous and invasive plant species in detriment of autochthonous ones (Holmes, 2001; Foster et al., 2009; Daws et al., 2013; Nussbaumer et al., 2016). Colonization and dominance of invasive species seem to be a common side effect in exploited mines where substrate fertility has increased above dystrophic levels (Silva et al., 2013).

5. CONCLUSIONS

The incorporation of sewage sludge into the mining substrate created an edaphic environment chemically distinct from the original soil of the study area. A plant community primarily composed of allochthonous and invasive species spontaneously recruited on such fertile environment in detriment to the plant species present in the remaining portions of Cerrado within the mined landscape. The edaphic environment built with sewage sludge acted as a filter in assembling a distinct plant community compared to the native Cerrado vegetation.

SUBMISSION STATUS

Received: 13 oct., 2017
Accepted: 12 mar., 2018

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