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Environmental recovery from deactivated open dumping using direct seeding of native and short life-cycle species

Recuperação ambiental em depósito de resíduos sólidos a céu aberto desativado usando semeadura direta de espécies nativas e de ciclo de vida curto

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Abstract
The present study aimed to evaluate the efficacy of recovering a solid waste deposit area, deactivated 17 years ago, using the no-seeding of native species of the Brazilian savannah and cover. We conducted the study between 2016 and 2018 in 1 ha with the dominance of exotic grasses *Urochloa decumbes* and *Melinis minutiflora*. We delimited four environments of 11m x 29m (319 m^2) with ten plots of 5 x 5m (25m²). The environments showed low concentrations of macronutrients and organic matter (OM). This study is relevant for scientific advancement and the practical resolution of socio-environmental problems, especially in a context where inadequate solid waste management continues to be a growing challenge. We found a lower establishment rate and survival percentage for Cerrado species, 2400 plants.ha^{-1} (3.26%) and 71300 plants. ha^{-1} (96.74%) of short life-cycle species. The most satisfactory procedure was the treatment that used density II + sowing in soil without manure. This research fills the gap in the literature on the recovery of solid waste deposits. This study's results can help manage and recover areas similar to this in other regions of the country.

Keywords: Cerrado; Invasive Grasses; Seed Mixture; No-Sowing.

Resumo
O presente estudo teve como objetivo avaliar a eficácia da recuperação de uma área de depósito de resíduos sólidos, desativada há 17 anos, por meio da não semeadura de espécies nativas do Cerrado e cobertura vegetal. O estudo foi conduzido entre 2016 e 2018 em uma área de 1 ha com dominância das gramíneas exóticas *Urochloa decumbes* e *Melinis minutiflora*. Foram delimitados quatro ambientes de 11m x 29m (319 m^2) com dez parcelas de 5 x 5m (25m²). Os ambientes apresentaram baixas concentrações de macronutrientes e matéria orgânica (MO). Esse estudo é relevante tanto para o avanço científico, quanto para a resolução prática de problema socioambiental, especialmente em um contexto em que a gestão inadequada de resíduos sólidos continua sendo um desafio crescente. Foi encontrada menor taxa de estabelecimento e porcentagem de sobrevivência para as espécies do Cerrado 2400 plantas.ha^{-1} (3,26%) e 71300 plantas.ha^{-1} (96,74%) de espécies de ciclo de vida curto. O procedimento mais satisfatório foi o tratamento que utilizou densidade II + semeadura em solo sem esterco. Esta pesquisa contribui para preencher a lacuna na literatura sobre recuperação de depósitos de resíduos sólidos. Os resultados deste estudo podem auxiliar na gestão e recuperação de áreas semelhantes a esta em outras regiões do país.

Palavras-Chave: Cerrado; Gramíneas Invasoras; Mistura de Sementes; Sem Semeadura.

1. Introduction

One of the biggest problems of contemporary society is related to the excessive generation of solid waste by human activities (Nascimento *et al.*, 2019). The amount of daily waste accompanies population growth, reaching increasingly alarming volumes (Kaza *et al.*,2018; Chen *et al.*,2020). The lack of planning or public policies for correctly disposing of

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these wastes negatively affects ecosystems at different scales (Varveková *et al.,* 2018; Devadoss *et al.,*2021; Morita et al., 2021).

Among the different types of solid waste treatment in Brazil, especially from domestic sources, the highest percentage of destinations is controlled landfills or dumps (Abrelpe, 2019; Chen et al., 2020; Morita et al., 2021). In addition, global guidelines point to the need for recycling and separating types of waste, among other processes, as a scenario for current regulation (Kaza et al., 2018; MOOC, 2020). However, it is necessary to propose ways to recover areas affected by solid waste, such as deactivated landfills and dumps (Kumar & Agrawal, 2020; Morita et al., 2021). In this sense, monitoring and managing solid waste deposits to recover affected areas are necessary (Erdogan et al., 2008; Lira et al., 2016).

Rehabilitation is an essential tool for activities related to forest restoration in sites that have already been degraded (Hobbs & Harris, 2001; Kumari et al., 2022). Its function is to repair productivity and natural services, in whole or part, from 'pre-disturbance' conditions (Ser, 2004; Mansourian, 2005). This can only be achieved sustainably by restoring ecosystem functions, even in unfavorable environmental conditions.

The use of direct seeding from a mixture of seeds of native trees combined with short life-cycle species has worked in the recovery of degraded areas (Raupp et al. 2020; Wang et al. 2021, Kumari et al. 2022). Its low cost and reasonable germination rates usually provide excellent results. When well executed, its use allows a vegetation cover quickly and plays an essential role in reducing erosion and conserving moisture (Maiti & Maiti, 2015).

In this context, we hypothesize that direct seeding could positively influence the recovery of a dump area deactivated for about 17 years in the municipality of Diamantina, Minas Gerais. Because of this, the present study aimed to (i) characterize the chemical attributes of the substrate in the recovery area, (ii) analyze the composition of the seed bank of the substrate in the recovery process, (iii) measure the dominant grass species by quantifying their biomass and (iv) evaluate the effectiveness of the seed mixture via direct seeding in degraded areas by solid waste.

2. Methodology

2.1 Characterization of the study area

The study was carried out in an area of 1 ha, at coordinates 18°12'18,85" S (latitude) and 43°34'9,12"O (longitude) (Datum WGS 84). It is located at the Federal University of the Jequitinhonha and Mucuri Valleys (UFVJM), municipality of Diamantina, Jequitinhonha Mesoregion, Minas Gerais (Figura 1).

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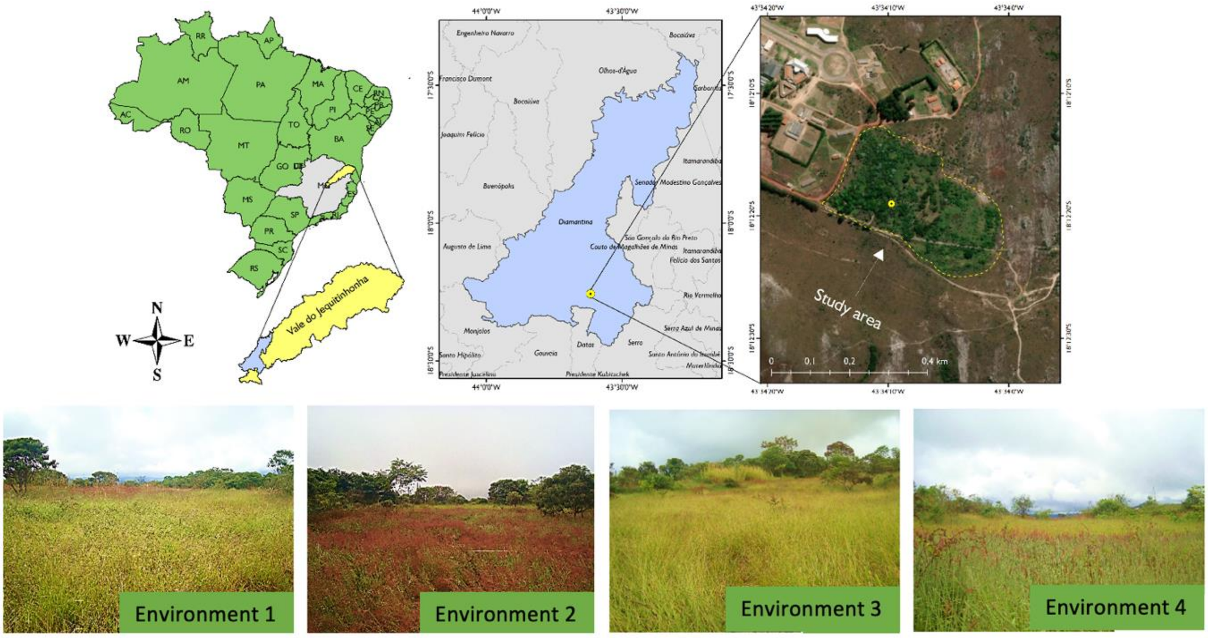
Figure 1. The study area is in the Diamantina, Jequitinhonha Valley, Minas Gerais, Brazil. Photographs illustrate the four environments of the deactivated dump before the interventions.



Source: Authors, 2025.

The region's climate is mesothermal type (Cwb), according to the international system of Köppen, with rainy summers and dry winters (Alvares et al., 2013). The predominant soils are Litholic Neosol and Cambisol, associated with quartzite and phyletic rocks of the Espinhaço Supergroup. It is located at about 1,380 m altitude, and the relief in the experimental area is flat to smooth elongated, but in the surroundings, the slopes can reach up to 60° (França et al., 2018). The typical vegetation cover of the region is characterized by the predominance of savanna, rural, and forest formations, constituting an ecotone between the Cerrado and the Atlantic Forest.

The study area was intended to dispose of municipal solid waste between 1993 and 2003. After deactivation, revegetation did not occur spontaneously, and most of the surface remained exposed (Miranda et al., 2012). Plant recomposition was performed by introducing seedlings of some tree species and exotic grasses *Urochloa decumbens* (Stapf) RD, Webster and *Melinis minutiflora* P. Beauv (Machado et al., 2013, Silveira et al., 2018). These invasive species are predominant in the area, further compromising the area's recovery nowadays.

Four environments (Figure 1) recovered by exotic grasses, *U. decumbens*, and *M. minutiflora*, were delimited throughout the area with dimensions 11m x 29m each, totaling 319 m^2, each containing ten plots of 5x5 m (25 m^2). Each environment had distinct characteristics (heterogeneous environments with the highest possible uniformity) but internal homogeneity (roughly similar plots). We followed the methodological sequence: (i) chemical analysis of the substrate, (ii) soil sampling for evaluation of the seed bank in the greenhouse, and (iii) biomass collection before the intervention. Chemical control of invasive grasses was performed in the experimental area. After these diagnoses and procedures, in March 2018, the seed mixture sowing experiment and evaluation began (Figure 2).

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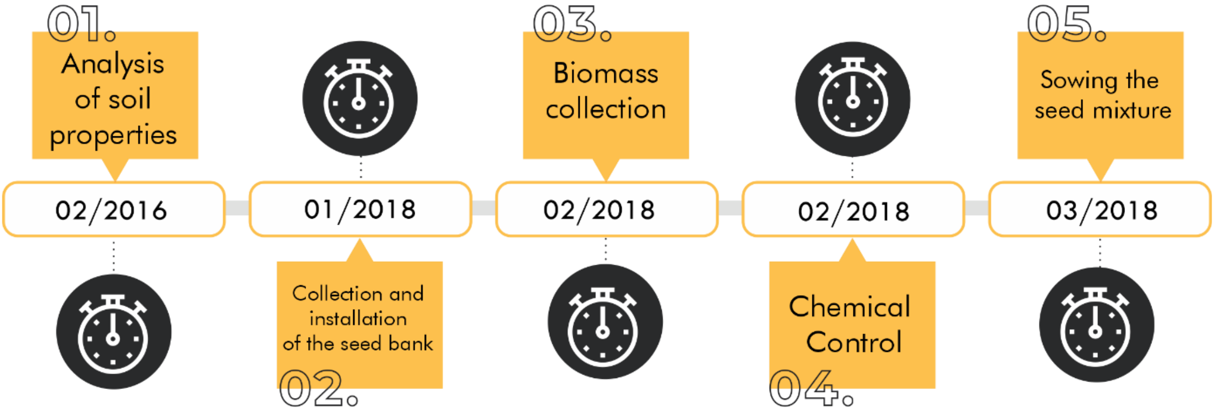
Figure 2. Stages of activities carried out during the trial period.



Source: Authors, 2025.

2.2. Data collected before the experiment: substrate, seed bank, Fresh and Dry Biomass

We collect a substrate sample from each environment composed of five at a 0-10 cm depth. Chemical analyses were carried out by the Soil Analysis Laboratory of the Federal University of Viçosa (UFV), following Embrapa's standards (2006). The variables analyzed were pH, P, K, Al^{3+}, Ca^{2+}, Mg^{2+}, H + Al, SB, CTC (t), CTC (T), V (%), OM, m (%), Zn, Fe, Mn, Cu, and B.

The seed bank consisted of 40 samples, one collection per plot, using a metallic jig (25 x 25 x 5 cm) and transported to the Integrated Center for Propagation of Seedlings of Forestry Engineering (CIPEF) of UFVJM and remained packed in a greenhouse under controlled daily irrigations, keeping its humidity close to the field capacity. They passed through a thick sieve (4.0 mm) to remove plant material, were homogenized, and packed in plastic trays of 0.004106 m^3, with a 4.0 cm layer of vermiculite to facilitate substrate drainage. The trays with substrate were allocated inside the greenhouse with a tray containing only vermiculite to verify the existence of contamination by external propagules.

Seedlings were counted monthly for the calculation of index and emergency velocity (IVE) and average monthly germination time (TMG) (Nakagawa, 1999) until the 6th month. The emergence criterion was considered as the appearance of the radicles and the propulsion of the bark, and it was annotated and dated according to appearance.

After 365 days, emerging seedlings were identified with material deposited in the Jeanine Felfili Dendrological Herbarium – HDJF of UFVJM. The classification of individuals in botanical families followed the Angiosperm Phylogeny Group IV system (APG IV, 2016). The diversity indexes of Shannon-Wiener (H'), equability (J') (Magurran, 1988), and the seed bank importance index (IVB) of each species (Caldato et al., 1996) were estimated. Species richness for the sampled environments was calculated using the Margalef index (DMg), which considers the numerical abundance of species in each geographic area. All procedures were performed using PAST 3.14 software (Hammer et al., 2016).

Fresh and dry biomass of the plants were harvested and measured to measure the biomass of the invasive grasses. We used a metallic jig (25 x 25 x 5 cm) allocated in each portion of the four environments, totaling 40 samples. The grasses were cut close to the substrate with scissors, and the other species were kept in place. After collection, the fresh material was packed in paper bags and weighed using a sample. Subsequently, they were dried

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in a greenhouse with forced air circulation at approximately 65° C for 72 hours until they reached the constant weight to evaluate dry biomass. The ANOVA and Tukey tests were performed for fresh and dry biomass variables. The box plot was also used to visualize the variables' behavior better. These procedures were performed in Environment R version 3.5.1 (R Core Team, 2018).

After the biomass collection of the invasive species *U. decumbens* and *M. minutiflora*, chemical control was performed so that they would not compromise the no-sowing experiment. To this end, in February 2018, the herbicide glyphosate (Roundup Original®) was applied as the most effective method to control these species in the area (Silveira et al., 2018). The application occurred when the grasses were approximately 1.0 m high. There was an interval of 15 days for the desiccation of biomass, and the dry material was kept in place and incorporated into the substrate with the aid of a tractor.

2.3 Direct Seeding

Direct seeding, consisting of the Cerrado tree (5 species) and short life-cycle (13 species) (Table 1), was performed during the rainy season in March 2018. The average precipitation during the post-sowing period was 19.4 mm, and minimum and maximum temperatures of 16.4° C and 25.6° C, respectively, according to National Institute of Meteorology (INMET) records.

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Table 1. Species used in direct seeding in degraded areas, Diamantina, Minas Gerais.

	F	Origin	Endemism	Specie identifies
CERRADO TREE SPECIES				
Asteraceae				
Eremanthus incanus (Less.) Less.	Tree	N	E	1
Bignoniaceae				
Anemopaegma arvense (Vell.) Stellfeld ex de Souza	Bush	N	NE	2
Calophyllaceae				
Kielmeyera coriacea Mart. & Zucc.	Tree	N	NE	5
Fabaceae				
Dalbergia miscolobium Benth.	Tree	N	E	3
Solanaceae				
Solanum lycocarpum A.St.-Hil.	Bush	N	NE	4
SHORT LIFE-CYCLE SPECIES				
Asteraceae				
Helianthus annuus L.	Grass	C	NE	12
Brassicaceae				
Raphanus sativus L.	Grass	NA	NA	16
Fabaceae				
Arachis pintoi Krapov. & W.C.Greg.	Erva	N	E	6
Cajanus cajan (L.) Huth	Arbusto	C	NE	11
Canavalia ensiformis (L.) DC.	Liana	C	NE	10
Centrosema pubescens Benth	Liana	N	NE	13
Crotalaria ochroleuca G. Don ou Crotalaria spectabilis Röth	Subarbusto	C	NE	9
Dolichos lablab L.	Liana	NA	NE	8
Mucuna aterrima (Piper & Tracy) Holland *or Mucuna pruriens* (L.) DC.	Liana	N	NE	15
Pueraria phaseoloides (Roxb.) Benth.	Liana	NA	NE	17
Stylosanthes capitata Vogel	Subarbusto	N	NE	19
Poaceae				
Lolium multiflorum L.	Erva	C	NE	7
Pennisetum glaucum (L.) R.Br.	Eva	NA	NE	14
Sorghum bicolor (L.) Moench	Erva	NA	NE	18

VF= Life form; N= Native; NA= Naturalized; C= Cultivated; E= Endemic; NE= Non-endemic
Source: Authors, 2025.

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In treatments, we applied two seed densities for Cerrado trees and short life-cycle species (Table 2). The treatments use manure, soil, and sawdust as filling materials for homogenization.

Table 2. Seed mixture densities for Cerrado trees and short life-cycle species in treatments in the degraded area, Diamantina, Minas Gerais.

	Density I		**Density II**	
Cerrado Tree Species	**Seeds (m²)**	**Seeds per plot**	**Seeds (m²)**	**Seeds per plot**
Eremanthus incanus	100	500	150	750
Anemopaegma arvense	10	50	20	100
Kielmeyera coriacea	5	25	10	50
Dalbergia miscolobium	10	50	20	100
Solanum lycocarpum	50	250	100	500
Short life-cycle species	5	25	10	50

Source: Authors, 2025.

The seed mixtures of each treatment were distributed by pitch. The experimental design was used in randomized blocks, containing ten treatments each following the nominations: T1 as Control without intervention; T2 - Control with manure; T3- Density I + sowing in soil with manure; T4 - Density I + sowing in soil without manure; T5- Density I + sowing with sawdust and manure; T6- Density I + sowing with sawdust without manure; T7 - Density II + sowing in soil with manure; T8- Density II + sowing in soil without manure; T9- Density II + sowing with sawdust and manure and T10 - Density II + sowing with sawdust and without manure.

At 90 days after sowing (June 2018), the establishment, survival, and botanical identification were evaluated through bibliographic references and Jeanine Felfili Herbarium of UFVJM. The identification of the species was based on the emerging seedlings with visible protophils. The phytosociological parameters of absolute density (AD) and absolute frequency (AF) were calculated (Müeller-Dombois & Ellenberg, 1974). The Durbin-Watson and Deviance test (ANADEV) submitted the other measures for waste independence analysis using generalized linear models (GLM) with the quasi-Poisson distribution. The choice of the GLM method occurred due to the absence of normality and homogeneity of variances by the Shapiro-Wilk and Bartlett tests, respectively. The test of multiple comparisons was that of Tukey–Kramer (HSD). All statistical analyses were performed with a 5.0% significance using software R (R Core Team, 2018).

3. Results

3.1 Features of the substrate, seed bank, fresh and dry biomass before direct seeding

All environments had very low to low concentrations of macronutrients, except for K in Environment 3, which showed a median concentration. Al scores were good to tolerable, Fe

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values were high, especially in environment 4, and OM had low amounts in all evaluated settings (Table 3).

Table 3. Physical-chemical analysis of the substrate in different environments of the Diamantina deactivated dump, Minas Gerais.

Attributes	Environments			
	1	**2**	**3**	**4**
pH[1]	4,6	4.4	4.8	4.9
P (mg/dm^3)[2]	0.8	1.3	2.3	2.5
K (mg/dm^3)[2]	30	26	51	37
Al^{3+} ($cmol_c/dm^3$)[3]	0.2	0.4	0.2	0.2
Ca^{2+} ($cmol_c/dm^3$)[3]	0.2	0.1	0.8	0.6
Mg^{2+} ($cmol_c/dm^3$)[3]	0.1	0	0.3	0.1
H+Al ($cmol_c/dm^3$)[4]	2.97	2.64	2.31	1.98
SB ($cmol_c/dm^3$)[5]	0.38	0.17	1.23	0.79
CTC (t)($cmol_c/dm^3$)[6]	0.58	0.57	1.43	0.99
CTC (T)($cmol_c/dm^3$)[7]	3.35	2.81	3.54	2.77
V(%)[8]	11.26	5.94	34.76	28.65
MO (dag/kg)[9]	1.86	1.55	1.86	1.65
m (%)	34.67	70.59	13.98	20.1
Zn (mg/dm^3)	0.9	0.5	1.4	3.1
Fe(mg/dm^3)	71.7	99.7	93.2	170.5
Mn(mg/dm^3)	1.4	0.4	2.9	5
Cu(mg/dm^3)	0.4	0.2	0.3	0.7
B(mg/dm^3)	0.1	0.1	0.1	0.1

[1]pH in H_2O 1:2.5; [2]Mehlich-1 Extractor; [3]KCl Extrator 1.0 mol/L; [4]CaOAc Extractor 0.5 mol/L. pH 7,0; [5]SB= $K^+ + Ca^{2+} + Mg^{2+}$; [6]Effective cation exchange capacity; [7]Cation exchange capacity at pH 7,0; [8] Base saturation index; [9]Organic matter (OM= C. org. x 1.724). **Source:** Authors, 2025.

Concerning the seed bank, the emergence speed index showed similar patterns in the germination of the species present in the seed bank of the degraded area (Table 4). The lowest values were found in the first 30 days for all environments, increasing and stabilizing at 150 and 180 days.

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Table 4. Emergence Speed Index (ESI) and Average Time to Germination (ATG) of the seed bank in different environments of the Diamantina deactivated dump, Minas Gerais

	30 days		**60 days**		**90 days**		**120 days**		**150 days**		**180 days**	
Environments	**ESI**	**ATG**	**ESI**	**ATG**	**ESI**	**ATG**	**ESI**	**ATG**	**ESI**	**ATG**	**ESI**	**ATG**
1	0.68	20.40	2.35	140.80	2.18	196.40	1.72	206.40	1.39	208.40	1.16	209.40
2	0.64	19.20	2.39	143.60	2.26	203.40	1.78	213.40	1.44	215.40	1.20	216.40
3	0.68	20.40	2.07	124.00	2.31	208.00	1.82	218.00	1.47	220.00	1.23	221.00
4	0.64	19.20	2.46	147.80	2.45	220.80	1.92	230.80	1.55	232.80	1.30	233.80

Source: Authors, 2025.

In 365 days, 4416 seedlings belonging to 22 species and ten botanical families were identified. There was a predominance of native or naturalized herbs, not endemic to the region, except for *Eragrostis rufescens* Schrad. ex Schult (Table 5).

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Table 5. Species sampled in the seed bank, the form of life (FL), origin, and phytosociological parameters: absolute density (AD); relative density (RD); absolute frequency (AF); relative frequency (RF), and Seed Bank Importance Value (SBIV) from Diamantina deactivated dump, Minas Gerais.

Family/Species	Environmental occurrence				FL	Origin	Phytosociological parameters				
	1	2	3	4			AD	RD	AF	RF	SBIV
Asteraceae											
Ageratum fastigiatum (Gardner) R.M.King & H.Rob.	x	x	x		B	N	70	5.22	75	5.77	10.99
Ageratum conyzoides	x	x	x		B	N	80	5.97	50	3.85	9.82
Emilia fosbergii Nicolson	x		x	x	E	N	80	5.97	75	5.77	11.74
Achyrocline satureioides (Lam.) DC.	x	x			E	N	30	2.24	25	1.92	4.16
Acanthospermum australe (Loefl.) Kuntze		x	x	x	E	C	70	5.22	75	5.77	10.99
Vernonanthura phosphorica (Vell.) H.Rob		x	x	x	U	C	70	5.22	50	3.85	9.07
Baccharis dracunculifolia DC.		x		x	B	N	10	0.75	25	1.92	2.67
Tagetes patula L.				x	E	N	10	0.75	25	1.92	2.67
Cyperaceae											
Cyperus sp.	x	x	x		E	N	60	4.48	50	3.85	8.33
Cyperus surinamensis Rottb.			x	x	E	N	60	4.48	50	3.85	8.33
Fimbristylis complanata (Retz.) Link	x	x			E	N	70	5.22	50	3.85	9.07
Kyllinga odorata Vahl	x				E	N	10	0.75	25	1.92	2.67
Bulbostylis hirtella (schrad.) Urb.	x				E	N	40	2.99	25	1.92	4.91
Eriocaulaceae											
Eriocaulaceae Martinov				x	E	N	20	1.49	25	1.92	3.41
Euphorbiaceae											
Ricinus communis L.		x		x	B	C	30	2.24	50	3.85	6.09
Fabaceae											
Crotalaria ochroleuca G. Don		x			Sub	N	30	2.24	25	1.92	4.16
Lamiaceae											
Hyptis suaveolens Poit.	x		x	x	Sub	N	110	8.21	75	13.98	22.19
Poaceae											
Melinis minutiflora P. Beauv	x	x	x	x	E	Na	140	10.45	100	7.69	18.14
Eragrostis rufescens Schrad. ex Schult*.		x	x		E	N	40	2.99	50	3.85	6.84
Polygalaceae											
Polygala paniculata L.	x		x		E	N	30	2.24	50	3.85	6.09
Portulacaceae											
Portulaca oleracea L.	x				E	N	20	1.49	50	3.85	5.34
Rubiaceae											
Diodella teres (Walter) Small	x	x	x		E	N	120	8.96	75	5.77	14.73

FL= Life Form; N = Native; Na = Naturalized; C = Cultivated; H = Herb; U = Underbrush; B = Bush; *- Endemic.
Source: Authors, 2025.

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The species that compose the seed bank predominantly belong to the Asteraceae, Cyperaceae, and Poaceae families. Among the species stood out, *Hyptis suaveolens* Poit., *Melinis minutiflora* P. Beauv, *Diodella teres* (Walter) Small, *Emilia fosbergii* Nicolson, *Ageratum fastigiatum* (Gardner) R.M.King & H.Rob. and *Acanthospermum australe* (Loefl.) Kuntze with the highest SBIV, covering a density of 590 ind ha^{-1}, corresponding to 44.02% of the total (Table 5).

Environment 1 seed bank showed higher density, reflecting the predominant presence of species with increased AF and SBIV in this environment (Table 6). Margalef's Richness Index (DMg) showed intermediate values, ranging between 4.43 and 3.91 (Table 6). Shannon Diversity Index was low (H' varied between 2.30 and 2.52). Pielou's Evenness Index values were similar between environments (Table 6).

Table 6. Phytosociological, diversity, and species richness parameters sampled in the seed bank of Diamantina deactivated dump, Minas Gerais. NS: number of species; AD: absolute density; RD: relative density; AF: absolute frequency and RF: relative frequency; DMg: Margalef's Richness; H': Shannon Diversity and J: Pielou's Evennes.

Environment	NS	AD	RD	Diversity and Richness		
				DMg	**H'**	**J'**
1	14	1480	27.61	4.43	2.52	0.99
2	13	1280	23.88	4.17	2.44	0.98
3	13	1440	26.87	4.02	2.37	0.92
4	12	1160	21.64	3.91	2.30	1.00

Source: Authors, 2025.

Concerning biomass, a significant difference was found between fresh and dry biomass production in the environment. Environment 2 was the only one that statistically differed from the others, presenting a lower average (Table 7).

Table 7. Medium values of fresh and dry biomass of the dominant species in four environments of the Diamantina deactivated dump, Minas Gerais.

Environment	Fresh biomass (kg ha^{-1})	Dry biomass (kg ha^{-1})
1	10724 ab	5119 ab
2	8964 c	4227 c
3	9210 b	6561 ab
4	9557 b	7313 a
CV (%)	**12,3**	**11,8**

Source: Authors, 2025.

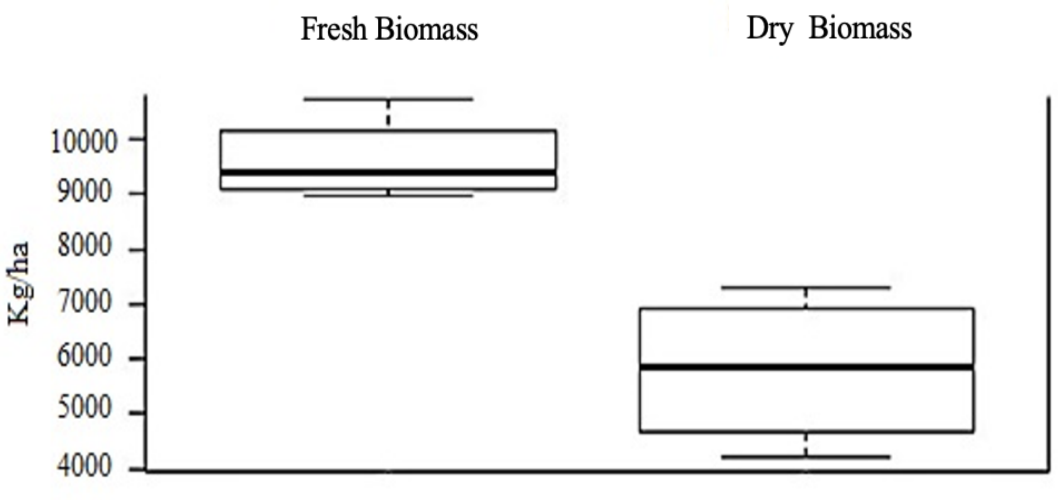
By the Box plot diagrams**,** it is possible to observe variations in the proportions of biomass found, with slight differences between the averages of fresh and dry biomass (Figure 3). The fresh biomass had a median of 961.37 g/m² (9613.7 kg ha^{-1}) varying between 896.4 g/m² and 1072.4 g/m² corresponding to 8964.1 kg ha^{-1}, and 10724.7 kg ha^{-1}. The dry biomass had an average of 580.5 g/m² (5805.1 kg ha-^{1}) and variation between 422.7 g/m² and 731.4 g/m²

https://doi.org/10.5281/zenodo.17409758

ISSN 2317-0611

equivalent to 4227.1 kg ha^{-1} and 7314.4 kg ha^{-1} for the material collected from the degraded area.

Figure 3. Box plot of fresh and dry biomass in kg ha^{-1} of the dominant species in Diamantina deactivated dump, Minas Gerais.



Source: Authors, 2025.

3.2 Direct Seeding

A total of 737 seedlings of species sown in the experiment area were observed, with 24 from Cerrado and 726 from short life-cycle species. The results per treatment indicated that the controls without intervention (T1) and with organic fertilization (T2) did not show the establishment of species from the seed mixture. The density and frequency of plants established by mixing seeds of Cerrado and short life-cycle species (T3 to T10) varied between treatments applied (Table 8).

https://doi.org/10.5281/zenodo.17409758

Table 8. Density and absolute frequency of plants established via seed mixture through different treatments, number of established plants, and survival rate at 90 days in the Diamantina deactivated dump, Minas Gerais.

Treatments	Cerrado tree species		Short life-cycle species	
	Absolute Density (ind. m^{-2})	**Absolute Frequency (%)**	**Absolute Density (ind. m^{-2})**	**Absolute Frequency (%)**
Control without intervention (T1)	0	0	0	0
Control with manure (T2)	0	0	0	0
Density I + sowing in soil with manure (T3)	12	30	34.8	740
Density I + sowing in soil without manure (T4)	4	30	33.6	730
Density I + sowing with sawdust and manure (T5)	4	10	31.6	980
Density I + sowing with sawdust without manure (T6)	16	30	26.4	640
Density II + sowing in soil with manure (T7)	0	0	35.6	1010
Density II + sowing in soil without manure (T8)	24	60	25.6	620
Density II + sowing with sawdust and manure (T9)	8	20	42.8	1060
Density II + sowing with sawdust and without manure (T10)	20	50	44.4	1150
Species establishment (plants.m^{-2})	2.4		71.3	
Species survival (%)	3.26		96.74	

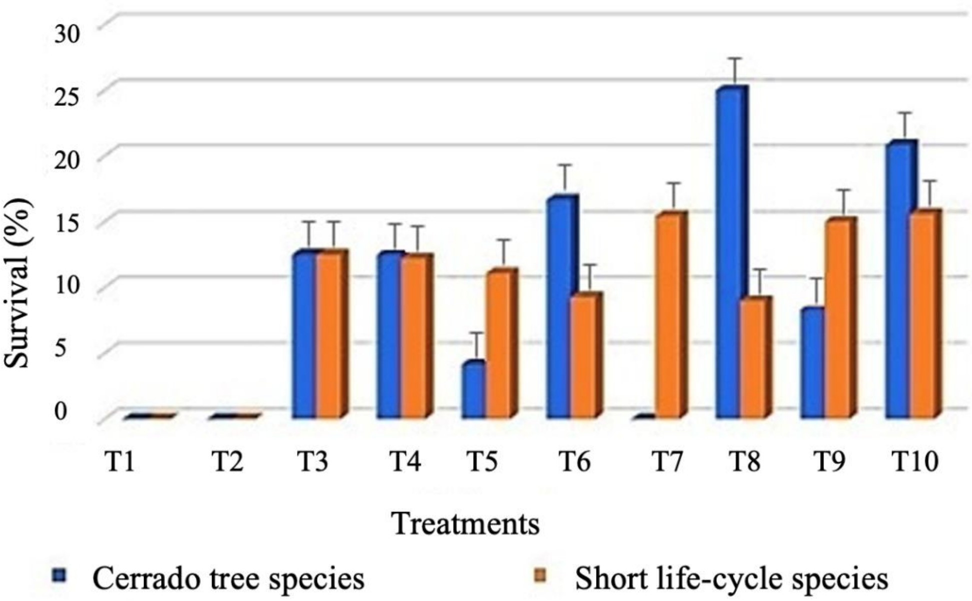
Source: Authors, 2025.

The parallel between treatments for short life-cycle and tree species demonstrates an egalitarian tendency in T3 and T4. Survival superiority of short life-cycle species occurred only at T7, T9, and T10, as well as for Cerrado species at T8 (Figure 4).

https://doi.org/10.5281/zenodo.17409758

ISSN 2317-0611

Figure 4. Survival of plants by treatment from the seed mixture composed of the Cerrado tree and short life-cycle species at 90 days of direct seeding in four environments of the Diamantina deactivated dump, Minas Gerais.



Source: Authors, 2025.

The total results represented relatively low initial seedling establishment values. It was observed that *E. incanus* had the highest number among the established Cerrado tree seeds. However, the *K. coriacea* was the species with the highest percentage of an initial establishment at densities 1 and 2. Among the short life-cycle variety, *R. sativus* and *C. ensiformis* were superior in the establishment (Figure 5).

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Revista Espinhaço, 2025, 16 (1)

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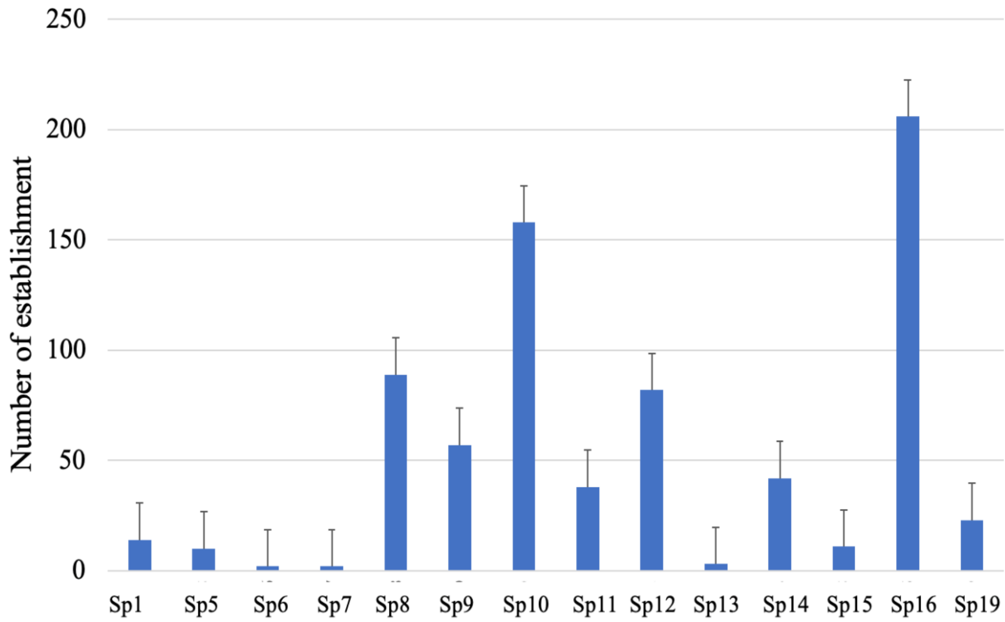
Figure 5. Cerrado and short life-cycle species



a) The establishment of Cerrado trees and short life-cycle species from the seed mixture for all treatments ate the Diamantina deactivated dump, Minas Gerais. Sp1- *E. incanus*; Sp2- *K. coriacea*; Sp6- *A. pintoi*; Sp7- *L. multiflorum;* Sp8- *D. lablab*; Sp9- *C. ochroleuca* ou *C. spectabilis*; Sp10- *C. ensiformis*; Sp11- *C. cajan*; Sp12- *H. annuus*; Sp13- *C. pubescens*; Sp14- *P. glaucum*; Sp15- *M. aterrima* ou *M. pruriens*; Sp16- *R. sativus*; Sp19- *S. capitata* ou *S. macrocephala*. As espécies Sp2- *A. arvense*; Sp3- *D. miscolobium*; Sp4- *S. lycocarpum*; Sp17- *P. phaseoloides* and Sp18- *S. bicolor* are not represented because they did not germinate. **Source:** Authors, 2025.

The germinated species were submitted to statistical tests. The premise of waste independence was fulfilled. Analysis of Deviance with the F test (Table 9) indicated a significant statistical difference between treatments regarding the relative densities of *E. incanus*, *K. coriacea*, *A. pintoi*, *L. multiflorum*, *C. pubescens* and *S. capitata* ($p \leq 0.05$).

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Table 9. Analysis of Deviance for species richness and abundance identified 90 days after experimental installation at the Diamantina deactivated dump, Minas Gerais.

Attributes	Environments *	Treatments	Waste	F Test	Total Average
	------------ *Deviance* ------------			***P***	
[1]Richness	13.79	5.13	10.12	0.2237	0.34
[1]Abundance	40.42	11.91	17.81	0.2034	0.75
[2]Richness	3.59	2.53	8.28	0.5166	5.75
[2]Abundance	48.16	28.60	114.79	0.6728	22.28
[1]*E. incanus*	183.71	121.23	53.12	0.0045	2.67%
[1]*K. coriacea*	109.46	92.48	41.09	0.0123	1.91%
[2]*A. pintoi*	24.64	43.79	13.66	0.0000	0.43%
[2]*L. multiflorum*	27.07	27.07	0.00	0.0000	0.31%
[2]*D. lablab*	66.25	29.43	167.18	0.7812	11.85%
[2] *C. ochroleuca*	66.01	34.03	165.22	0.6472	7.00%
[2]*C. ensiformis*	9.12	39.21	139.24	0.4910	22.02%
[2]*C. cajan*	38.48	93.05	140.65	0.0841	4.36%
[2]*H. annuus*	198.31	65.44	133.94	0.1529	9.80%
[2]*C. pubescens*	7.66	33.77	10.13	0.0000	0.33%
[2]*P. glaucum*	40.05	102.04	178.80	0.0918	5.97%
[2]*M. aterrima*	27.15	36.46	56.54	0.0858	1.41%
[2]*R. sativus*	45.59	23.84	163.98	0.8257	29.00%
[2]*S. capitata*	65.18	194.34	128.48	0.0037	2.93%

[1] Cerrado tree species and [2] short life-cycle species.

Source: Authors, 2025.

The highest relative frequency (RD) of individuals grouped as Cerrado trees was found in treatment T6 (*E. incanus* and *A. arvense* and RD of 8.14%) (Table 10).

https://doi.org/10.5281/zenodo.17409758

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Table 10. Relative Density (RD) of species *Eremanthus incanus* (SP1), *Kielmeyera coriacea* (SP2), *Arachis pintoi* (SP3), *Lolium multiflorum* (SP4), *Centrosema pubescens* (SP10) and *Stylosanthes capitata* (SP14) identified at 90 days after experimental installation at the Diamantina deactivated dump, Minas Gerais.

Treatment	SP1		SP2		SP3		SP4		SP10		SP14	
	---------------------------------- % ----------------------------------											
T3	7.50	a	0.00	c	0.00	b	0.00	c	0.00	b	0.00	c
T4	2.00	bc	4.17	a	0.00	b	0.00	c	0.00	b	13.28	a
T5	0.00	c	0.78	bc	2.78	a	0.00	c	0.00	b	6.68	b
T6	4.55	ab	3.59	ab	0.00	b	0.00	c	2.15	a	0.00	c
T7	0.00	c	0.00	c	0.68	b	1.19	b	0.00	b	0.00	c
T8	6.82	a	0.00	c	0.00	b	0.00	c	0.00	b	2.70	bc
T9	0.49	c	0.49	bc	0.00	b	0.00	c	0.49	b	0.00	c
T10	0.00	c	6.25	a	0.00	b	1.25	a	0.00	b	0.81	c

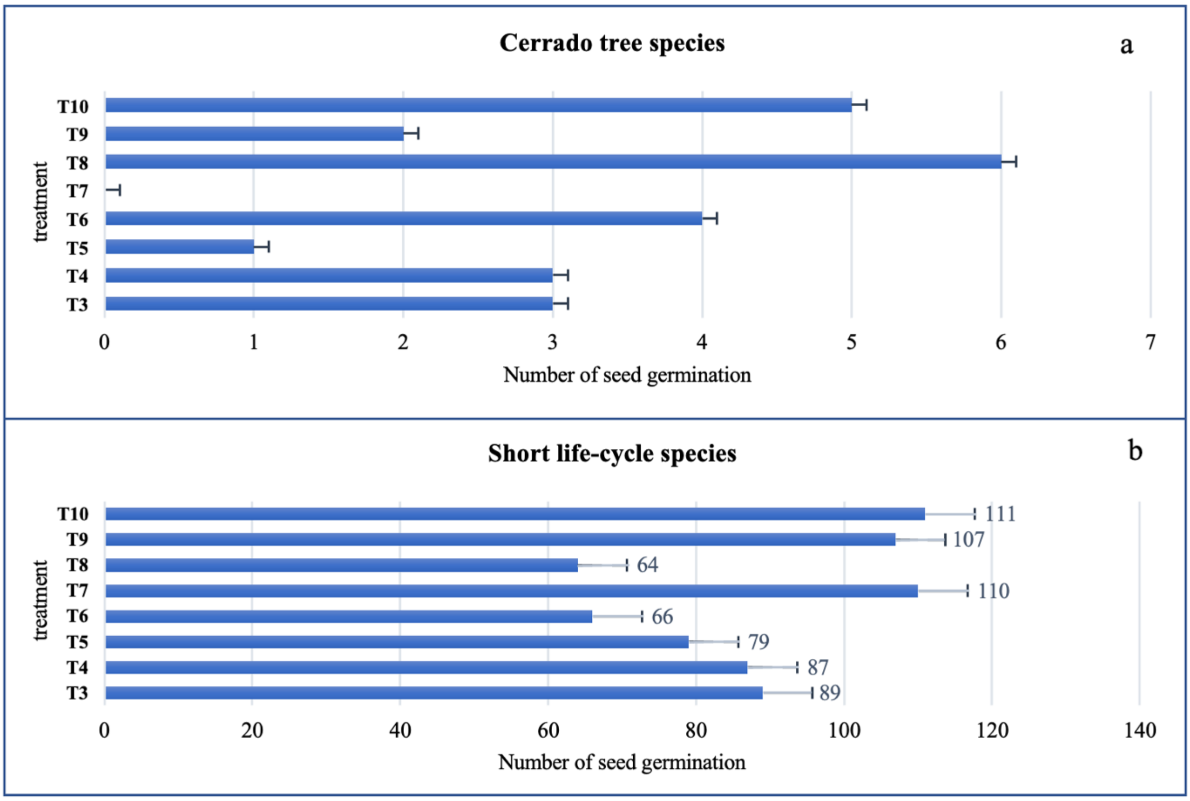
Averages followed by the same letter are not differentiated by the Tukey-Kramer test (HSD) at 5% significance.
Source: Authors, 2025.

The T8 treatment obtained a better initial establishment with the Cerrado tree species, with six seed germination. T10 revealed the highest number of seedlings from non-invasive individuals (111) and the Cerrado (5), totaling 116 (Figure 6a, b). There was greater germination in density II treatments (T7 to T10), with 405 individuals, compared to density I treatments (T3 to T6), with 332. Regarding the filling material, it was observed that the seeds homogenized with sawdust had more establishments, 375 individuals. The use of manure in some portions provided more significant amounts of germinated seeds in most treatments, except for T10.

https://doi.org/10.5281/zenodo.17409758

ISSN 2317-0611

Figure 6. Initial establishment of seedlings by treatment: (a) Cerrado tree species and (b) short life-cycle species at the Diamantina deactivated dump, Minas Gerais.



Source: Authors, 2025.

The results point to environment 4 with the lowest total number of seedlings per m^2 without germination of Cerrado seed species. Environment 3 presented the highest number of seedlings per m^{2,} and Environment 2 with the highest number of germinated Cerrado seeds (Table 11).

Table 11. General aspects of initially established seedling species in the four environments of the Diamantina deactivated dump, Minas Gerais.

Seed Germination	**Environment**			
	1	**2**	**3**	**4**
Cerrado tree species	3	20	1	0
Short life-cycle species	216	130	232	135
Total number of seed germination	219	150	233	135
Total number of seed germination per m²	0.69	0.50	0.73	0.42
Area of each environment (m²)	319			

Source: Authors, 2025.

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4. Discussions

4.1 Diagnosis of the area before the direct seeding

In our study, most of the elements for the four environments showed low levels, especially P and K levels, a result associated with areas of sandy soils in quartzitic Rupestrian Grassland (Lira-Martins et al., 2022). However, it is notable that the average values for these elements, obtained in 2017, are higher than those obtained in 2007 (Miranda et al., 2012). This result indicates an increase in substrate fertility requirement, even if not very significant, and therefore acts positively on the regeneration and fixation of local vegetation (Shaw et al. 2020).

The low values of most nutrients (high concentrations of Fe and acidic pH) are related to the deposition of waste in the environment. However, there are nearby places with high concentrations of Fe. The low nutritional availability/accumulation worsens as the most diverse materials decompose, which, for the most part, promotes chemical changes (incorporation of heavy metals and other toxic elements, contamination of surface water and groundwater), physical (modifications in the structure and differences in the local topography) and biological (loss of organic matter and attraction of animals that did not exist before).

The low levels of organic matter (OM) found in this work were also verified by Machado et al. (2013); however, when compared to 2007 values (Miranda et al., 2012) (0.1 dag kg^{-1}), it is noted that this parameter has shown positive changes throughout the last ten years in the study area. Substrates with low levels of organic matter commonly affect nutrient availability, cation-exchange capacity, and the complexation of toxic elements (Bayer & Mielniczuk, 1999). These variables can be a factor that directly affects plant development (Erdogan et al., 2008).

In general, the chemical parameters of the study area substrate have gradually increased in nutritional value for vegetation compared to older data (Miranda et al. 2012; Machado et al. 2013). However, ecophysiological attributes of exotic grasses support their development in areas that have suffered high disturbance (Melo Júnior et al., 2015, Vaverková et al., 2019). In this sense, its control becomes indispensable until other plants can establish and develop effectively (Silveira et al., 2018).

Concerning the seed bank of the environments, species classified as “herbs” constitute most of the plants found and usually comprise one of the main components of the soil seed bank, common in surveys of solid waste deposits (Sanou et al., 2018; Varveková et al., 2019). The low presence of other individuals leads to reduced diversity, directly affecting the processes of natural regeneration and ecological succession (Dairel & Fidelis, 2020).

The ecological interaction in a community can be positive (facilitation) or negative (competition) (Laurent et al., 2017). We cite as a negative interaction the invasive species *M. minutiflora* recurrent in the seed bank of the area with a record of infestation for more than eight years. The species has high adaptability in the most diverse circumstances, and its dispersion mechanisms are highly effective at short and long distances; in addition to reaching early maturity, they have longevity and a high growth rate (Simberloff, 2014; Zenni et al., 2016). These characteristics show the damage of the occupation of these invasive species after disturbances in the Cerrado biome (Strassburg et al., 2017).

We verified a significant increase in diversity and evenness values compared to the seed bank's results obtained in 2010, both for the dry and rainy seasons (Machado et al., 2013). This fact evidences a positive and progressive condition regarding the quality of the landfill’s seed bank. However, the values found in 2018 indicate low richness and diversity compared to other

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ISSN 2317-0611

degraded areas in the natural regeneration of rupestrian Cerrado near the study area (H' from 2.742 to 3.921) (Amaral et al., 2020). This fact allows us to infer that the dense formation of exotic grasses can negatively affect the diversity of native species (Dairel & Fidelis, 2020).

The total dry matter profit was higher in all environments than Miranda et al. (2012) values for *U. decumbens* (3610 kg ha^{-1}). The medium values (5805 kg ha^{-1}) were also higher than those observed in other species of forage grasses verified by those mentioned above authors. The relationship between grass biomass and the richness and density of woody species has been negative for many years in studies in degraded areas (Fragoso et al., 2017).

The dominance of invasive exotic plants is challenging in recovering degraded ecosystems (Durigan et al., 2013, Silva &Vieira, 2017, Sampaio et al., 2019). The two dominant species, when established, compete strongly with the native community. There are indications that *M. minutiflora* sets itself first in the areas, mainly in open environments, followed by the arrival of the more aggressive *U. decumbens* (Silva & Vieira, 2017). In places with a high predominance of herbaceous individuals, grasses become a permanent problem (Durigan et al., 2013).

4.2 The Direct seeding

Environment 4 presented the lowest rate of fixed individuals considering the treatments, which may be related to the significant presence of *R. communis.* Studies have demonstrated its potential in phytoremediation for heavy metals in mining environments (Peixouto et al. 2021) and its positive presence in the study area. However, the species may have a higher amount of dry biomass of exotic dominant species. Another factor that may have affected is the higher concentrations of Iron, Manganese, Zinc, and Copper. Iron presented a much higher value when compared to other environments. In addition, factors related to poor soil structure, micro and macronutrient deficiency, compaction of the upper cover, low water retention capacity, and existence of gases and toxic components, such as heavy metals, are the main aspects that limit seed germination (Sheoran et al., 2010, Rahman et al., 2013, Chen et al., 2015).

We observed the low seedling establishment of Cerrado tree species compared to short life-cycle vegetables. This result was expected, but its rapid growth, promoting soil cover, hinders the colonization actions by invasive grasses (Ruadd et al., 2020), favoring the production of organic matter and soil fertility (Koda et al., 2013). Thus, their function would be to promote environmental improvements to facilitate the establishment of tree species.

The best results were treatments with a density II per plot for Cerrado species. Well-executed high-density seeding increases relative native coverage (Schneemann and Mcelhinny, 2012, Sampaio et al., 2019). However, the limitation of high-density use is related to vulnerability to climatic extremes, low growth rates in the first years, and invasive grasses (Palma & Laurance, 2015, Silva et al., 2015, Passaretti et al., 2020).

High germination rates of the species are conditioned to environmental, morphological, and genetic factors. Large seeds (more significant reserves) withstand unfavorable conditions for longer, increasing their survival (Palma & Laurance, 2015; Jimenez-Alfaro et al., 2016). Smaller seeds colonize the site quickly, and their thin cover contributes to germination and water absorption in the initial periods (Garcia-Orth & Martinez-Ramos, 2008, Tunjai & Elliott, 2012). However, with soil cover, the conditions for the germination of native species in the Cerrado may not arise (Silva & Vieira, 2017). These observations help in choosing the best species to be used.

https://doi.org/10.5281/zenodo.17409758

The use of manure as a nutrient source is an affordable and efficient alternative in the initial processes of seedling establishment (Silva et al. 2015). This method and direct seeding in solid waste disposal sites are little known but promising and recommended for the recovery of areas similar to the one in this study (Resende & Pinto, 2013).

In recovery processes, there is a search for alternatives that generate good results at low cost. With direct seeding, these two assumptions can be satisfied (Wallin et al., 2009, Sampaio et al., 2019), in addition to significant reductions in final expenses for recovery (Cole et al., 2011, Raupp et al., 2020). The costs associated with each technique must be considered when planning the restoration (Holl & Aide, 2011).

The richness and abundance of Cerrado tree species and the short life-cycle vegetables remained constant between treatments, a fact that may be related to aspects inherent to the environmental conditions of the areas. On the other hand, the studied treatments had different effects on the relative density of some species. The treatment that included density I and sowing with sawdust without manure favored the relative density of tree species *E. incanus* and *K. coriacea*. *E. incanus is* a species with superiority in colonizing degraded areas in the region (Terra et al. 2017). *K. coriacea* provided satisfactory germination results in Cerrado areas (Raupp et al. 2020). This result provides evidence that the site supplied the nutritional demand of these species during the experimental period, not requiring an external source of organic compost.

The short life-cycle vegetables, in particular *A. pintoi, L. multiflorum, C. pubescens,* and *S. capitata* had different behaviors between treatments. As recovery plans should be low-cost and as close as possible to the original plant formation (Raupp et al. 2020), the T8 treatment is recommended for further studies.

Our results provide positive information on mitigating impacts in areas with waste. There is a clear need for advances in the science of recovery of sites used as solid waste deposits. Substrate characteristics and the predominance of invasive exotic plants are reported as significant obstacles in efforts to recover and distribute native species via direct seeding in degraded ecosystems (Martins et al., 2011, Dairel & Fidelis, 2020). The use of short life-cycle vegetables added to the mulch resulting from the chemical effect acted in the control of *U. decumbes* and *M. minutiflora* through shading and competition. Thus, it increases the chances of survival and development of native and endemic species (Pereira et al., 2013, Raupp et al., 2020).

5. Conclusions

The presence of solid waste negatively influences the recovery of the area of this study, its substrate, and the plant species present in the area. The four environments analyzed showed similar fertility characteristics, such as high acidity pH, low concentrations of organic matter, and most macro and micronutrients.

The seed bank in the study area is predominantly composed of herbaceous species, many invasive, with a lower density of propagules from shrubs and tree plants, which interferes with the fixation, establishment, and survival of native individuals. In this sense, the use of techniques to contribute to the increase of seeds of local species is recommended.

The species *E. incanus K. coriacea* should be considered in future studies on the recovery of dumps and landfills in environments similar to this work. In the case of a mixture of short life-cycle species seeds, the association with *R. sativus* and *C. ensiformis* are viable. Based on the premises of the work, the most satisfactory procedure was the T8 treatment since

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there was a higher germination rate of tree species from the Cerrado and good germination of short life-cycle species.

As noted, studies on the advantages of seed mixing, although promising, have still been developing in environments, and more research is needed to provide detailed information on the behavior of some plants and their potential in deactivated dumb conditions.

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