

Recovering vegetation cover in a degraded bare area within the Cerrado, the Brazilian savanna

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ABSTRACT

1. Since the 1960s, large areas of the Cerrado biome have been converted for agriculture, livestock, infrastructure and mining, resulting in severe fragmentation and ecosystem degradation. The construction of hydroelectric power plants intensifies these impacts by removing vegetation and soil, often exposing compacted subsoil layers up to 10 m deep, which strongly limits natural regeneration and demands active recovery strategies.
2. This study evaluated the recovery of a severely degraded Cerrado area through soil mechanical movement and the incorporation of organic residues (macrophytes and biochar), combined with the introduction of native seedlings. Spontaneous plant species were surveyed 12 and 36 months after the start of the recovery process, and effectiveness was assessed based on species richness and plant origin.
3. Vegetation surveys conducted after 12 and 36 months revealed substantial colonization, with a total of 72 plant species established within three years of the recovery interventions.
4. Of the recorded species, 65 were native and seven were non-native. Colonization was enhanced by the rupture of the sealed surface, reduction of soil compaction and seedling introduction, as well as by zoochorous dispersal and propagule input from nearby vegetation fragments.
5. Overall, the applied recovery methods demonstrate that mechanical soil treatment combined with organic residue inputs can effectively initiate ecological processes and accelerate vegetation recovery in severely degraded subsoil areas of the Cerrado biome.

[Keywords: spontaneous vegetation, dispersal syndromes, degraded area, Fabaceae]

RESUMEN. Recuperación de la capa vegetal en una zona desnuda degradada del Cerrado, la sabana brasileña

1. Desde la década de 1960, grandes extensiones del bioma del Cerrado se han destinado a la agricultura, la ganadería, la infraestructura y la minería. Esto fragmentó y degradó gravemente el ecosistema. La construcción de centrales hidroeléctricas intensifica estos impactos al eliminar la vegetación y el suelo, dejando a menudo al descubierto capas de subsuelo compactadas de hasta 10 m de profundidad, lo cual limita la regeneración natural y exige estrategias de recuperación activas.
2. Este estudio evaluó la recuperación de una zona muy degradada del Cerrado mediante el movimiento mecánico del suelo y la incorporación de residuos orgánicos (macrofitas y biocarbón), combinados con la introducción de plántulas autóctonas. Se estudiaron las especies vegetales espontáneas 12 y 36 meses después del inicio del proceso de recuperación, y se evaluó la eficacia en función de la riqueza de especies y el origen de las plantas.
3. Los estudios de vegetación realizados después de 12 y 36 meses revelaron una colonización sustancial, con un total de 72 especies vegetales establecidas en los tres años siguientes a las intervenciones de recuperación.
4. De las especies registradas, 65 eran autóctonas y 7 no autóctonas. La colonización se vio favorecida por la ruptura de la superficie sellada, la reducción de la compactación del suelo y la introducción de plántulas, así como por la dispersión zocórica y la aportación de propágulos procedentes de fragmentos de vegetación cercanos.
5. En general, los métodos de recuperación aplicados demuestran que la mecanización del suelo, combinada con la incorporación de residuos orgánicos, puede iniciar eficazmente procesos ecológicos y acelerar la recuperación de la vegetación en zonas de subsuelo degradadas del bioma del Cerrado.

[Palabras clave: vegetación espontánea, síndromes de dispersión, área degradada, Fabaceae]

INTRODUCTION

The Cerrado, the vast and biodiverse Brazilian tropical savanna, covers 2039386 km² and represents 24% of the national territory (Sawyer et al. 2018; Sano et al. 2019). It is recognized as one of the world's biodiversity hotspots, areas of crucial importance for global biodiversity conservation. This recognition stems from its high species richness, endemism and significant threat levels (Sloan et al. 2014). However, since the 1960s, areas of the Cerrado have been converted into agricultural lands, livestock pastures and infrastructure such as roads and hydroelectric dams (Bittar 2011; Parente et al. 2021).

This conversion has led to significant fragmentation of the Cerrado ecosystem, negatively affecting its biodiversity and ecological balance. Furthermore, deforestation is the main cause of biodiversity loss (Giam 2017) and remains a major threat to continental biomes, as highlighted by Convention on Biological Diversity (2020). In fact, the Cerrado has already lost more than 1000000 km², representing more than 50% of its original area (INPE 2020).

The construction of a hydroelectric dam between the municipalities of Ilha Solteira (SP) and Selvíria (MS) resulted in the removal of vegetation and soil A and B horizons across extensive areas, with cuts reaching depths of up to 10 m (Alves et al. 2012). In this situation, the Cerrado exhibits low potential for natural regeneration (Durigan et al. 2011). In soil-stripping areas (0.20 m deep), the regeneration potential is low, and the severity of soil disturbance negatively affects the resprouting ability of deciduous forest trees (Ferreira et al. 2017). In these areas, the use of heavy machinery has left compacted subsoil exposed at the surface, decreasing water infiltration capacity (Rodrigues et al. 2007). Additionally, organic matter and nutrient availability are low (Alves et al. 2012; Rodrigues et al. 2007; Liu et al. 2018). Furthermore, the lack of a seed bank and of underground structures (e.g., roots, xylopodia and tubers), which would facilitate vegetation regrowth—a critical process for Cerrado restoration (Buisson et al. 2019; Pilon et al. 2021)—, exacerbates the low regeneration potential.

To recover these degraded areas, it is necessary to improve both the edaphic conditions of the soil and the vegetation cover

(Pellizzaro et al. 2017). Degraded soil and the reduction or absence of vegetation cover due to anthropogenic activities (i.e., agriculture, grazing, mining, urban development) (Ochoa et al. 2016; Russell and Ward 2016) lead to a loss of soil quality and reduced functionality. This resulted in the depletion of ecosystem services such as nutrient cycling and water-holding capacity (Gaikwad et al. 2023). In this situation, human-induced revegetation actions become very important (Chazdon 2013), as do seeds dispersed by wind (anemochory) and fauna (zoochory) (Sartorelli 2007; Correa et al. 2015), in order to rehabilitate degraded areas and recover, at least partially, ecosystem functions and services (Hobbs and Harris 2001). This is the case even if the edaphic difficulties of restoring the pristine vegetation lead to the establishment of a novel ecosystem (Buisson et al. 2019).

To improve soil conditions in compacted areas, it is necessary to use mechanization to break the surface sealing and compaction present in the superficial soil layer (Peixoto et al. 2020). In addition, introducing organic matter—which is typically depleted in degraded areas—can be achieved through the use of residues such as macrophytes (Azevedo et al. 2022) and ash from sugarcane bagasse (Bettiol et al. 2023). Revegetation can also help to improve soil structure (Xiao et al. 2022), facilitate water infiltration, increase soil moisture and introduce organic matter, influencing the microbial community (Bezemer et al. 2006; Kumar et al. 2010). These processes may accelerate soil rehabilitation by enhancing edaphic conditions (Bienes et al. 2016).

The use of seedlings for revegetation is particularly recommended for areas where soil conditions (i.e., soil carbon and nitrogen, soil density and water infiltration capacity) were negatively affected, resulting in soil without vegetation cover or a bare soil (Stumpf et al. 2018; Xiao et al. 2022) that is exposed to erosive processes (Rodrigues et al. 2007; Xiao et al. 2022). Planting seedlings can contribute to natural regeneration (Le et al. 2014), especially when native species are used, as their chances of survival are greater because they are better adapted to the environmental conditions of the area (Tang and Li 2014; Ilunga et al. 2015).

Over time, the seedlings can attract seed dispersers, facilitating both the arrival of new seeds and their survival (Reid et al. 2015). Furthermore, the presence of natural vegetation fragments in the surrounding

area can also contribute to regeneration by providing a source of seeds for dispersal (Ferreira et al. 2010; Santos et al. 2020). This propagule pressure is an important factor in ensuring species richness, especially in areas where regrowth is hindered by environmental degradation.

Given that the substrate to be restored consists of exposed subsoil, largely devoid of significant contributions from roots, underground storage organs, seed banks or other propagules, the emergence and establishment of spontaneous vegetation—and its species richness—will serve as an indicator of the ongoing recovery process. The aim of this study was to identify the species of spontaneous plants that colonized a degraded area 12 and 36 months after the start of a recovery process involving the mechanical movement of soil and the incorporation of residues materials (macrophytes and ash). The effectiveness of the recovery process was evaluated based on species richness and plant origin.

MATERIALS AND METHODS

This study was carried out under field conditions in the municipality of Selvíria (MS), at the experimental farm of the School of Engineering, São Paulo State University

(Unesp). The area was degraded in the 1960s during the construction of a hydroelectric power plant (HPP). This persisted until 2011 due to the intensity of the impact (Figure 1). It is important to mention that there are fragments of the Cerrado in the process of regeneration in the surrounding area (Figure 2b,c).

An area of 3.4 ha, characterized by bare subsoil since 1960s and located on the right bank of the Paraná River—downstream of the HPP (20°23' S - 51°24' W)—was selected for this study, and has been undergoing the recovery process since 2011. In this area, treatments have been carried out to create edaphic conditions to support the native vegetation, in this case, the Cerrado (Figures 1 and 2a,b) (SEPLANCT/MS 1990; Calgaro et al. 2015).

The experimental design was randomized blocks, in a 3 x 4 factorial scheme, with the application of three doses (0, 16 and 32 t/ha) of dried aquatic macrophytes (MAC) and four doses (0, 15, 30 and 45 t/ha) of biochar from sugarcane bagasse (BCR). Three repetitions of each treatment were set up, which resulted in 36 plots of 20 m x 30 m (600 m²), separated from each other by five-meter-wide lanes.

Before the mechanical preparation of the experimental area (Figure 2a), the bare subsoil

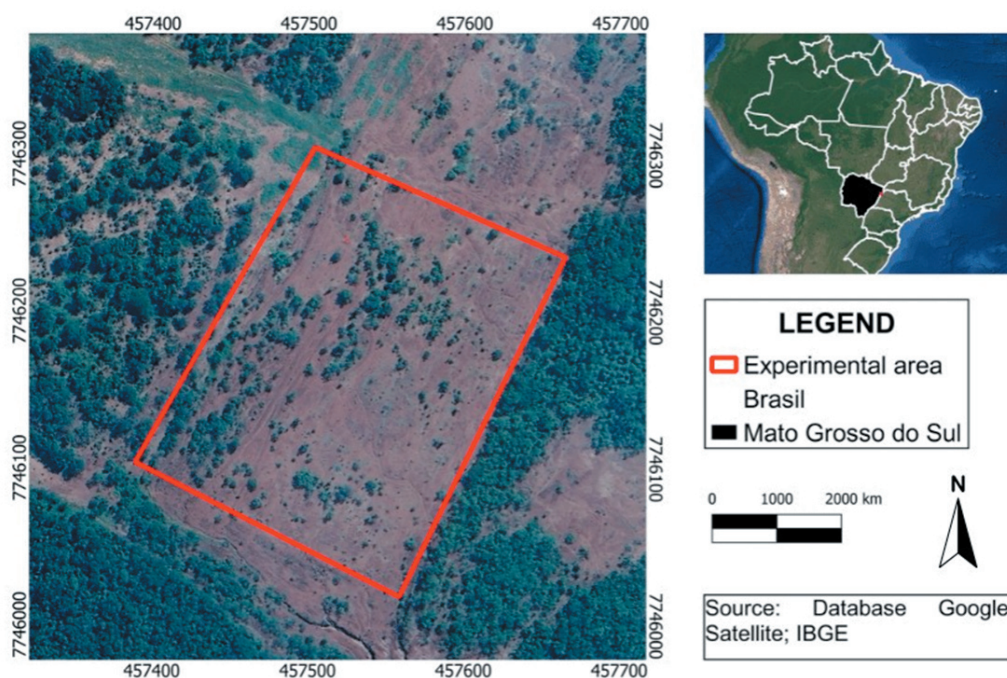


Figure 1. Location of experimental area.

Figura 1. Ubicación del área experimental.

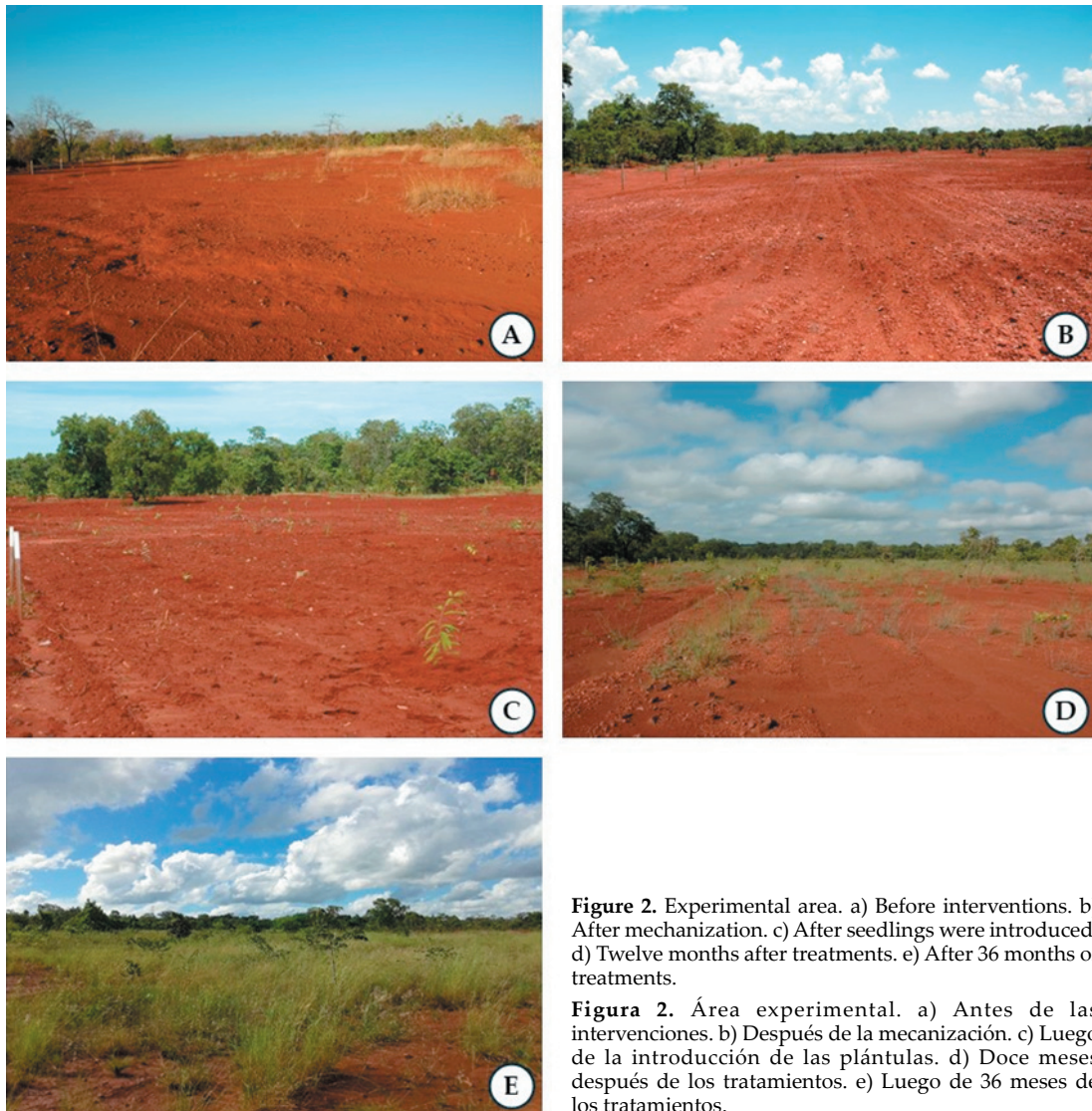


Figure 2. Experimental area. a) Before interventions. b) After mechanization. c) After seedlings were introduced. d) Twelve months after treatments. e) After 36 months of treatments.

Figura 2. Área experimental. a) Antes de las intervenciones. b) Después de la mecanización. c) Luego de la introducción de las plántulas. d) Doce meses después de los tratamientos. e) Luego de 36 meses de los tratamientos.

without intervention (BSWI) was analyzed, at a depth of 0.0-0.2 m, with three repetitions, for texture (pipette method) (Gee and Or 2002), bulk density (volumetric core) (Teixeira et al. 2017) and total organic carbon (loss on ignition method) (Ben-Dor and Banin 1989). The same analyses were performed in a conserved Cerrado (CCER), near the experimental field (20°21' S - 51°23' W) to have a reference of soil edaphic conditions under a conserved situation (Table 1). However, an assessment of the existing vegetation was made prior to the establishment of the treatment and almost nothing was reported; the vegetation was absent in the BSWI.

After the BSWI was analyzed, the area was harrowed (heavy harrow, 0.40 m deep) to break up the surface layer, and then chiseled (0.37 m deep). The residues (MAC and BCR)

were distributed with a spreading machine and incorporated with a medium harrow (0.30 m deep). The MAC consisted of a mixture of aquatic macrophyte species, including *Egeria densa* Planch., *Egeria najas* Planch., *Ceratophyllum demersum* L., *Eichhornia azurea* Kunth, *Eichhornia crassipes* (Martius) Solms-Laubach, *Pistia stratiotes* L. and *Typha latifolia* L. (species composition follows Thomaz et al. 2008). The macrophytes were collected from the reservoir of the Jupia Hydroelectric Power Plant (HPP) and were sun-dried for 120 days before use. The BCR was collected from Alcoolvale - Açúcar e Alcool Ltda., in Aparecida do Taboado (MS), Brazil. This residue was sun-dried for 30 days before use.

In November 2011, the residues were incorporated into the soil and the area

Table 1. Sand, silt and clay, bulk density and total organic carbon from bare subsoil without intervention (BSWI) and conserved Cerrado (CCER), F values, coefficients of variation (CV), mean bulk density (BD) and total organic carbon (TOC) after 36 months of intervention.

Tabla 1. Arena, limo y arcilla, densidad aparente y carbono orgánico total del subsuelo desnudo sin intervención (BSWI) y del Cerrado conservado (CCER), valores de F, coeficientes de variación (CV), densidad aparente media (BD) y carbono orgánico total (COT) luego de 36 meses de intervención.

Properties	BSWI	CCER	Source of variation	BD Mg/m ³	TOC Mg/g
Sand (%)	44	62	MAC	4.170*	9.955**
Silt (%)	10	07	BCR	4.223**	3.503*
Clay (%)	46	31	MAC X BCR	1.987 ^{ns}	0.964 ^{ns}
Bulk density (g/cm ³)	1.66	1.23	CV (%)	6	14
Total organic carbon (mg/g)	22.79	35.73	Average	1.39	25
			MAC		
			0	1.41b	23b
			16	1.39ab	26a
			32	1.35a	27a
			BCR		
			0	1.43	23
			15	1.39	26
			30	1.35	26
			45	1.37	25
				$\hat{Y}_{BD}^{**} = 1.42 - 0.0016x, R^2 = 0.7726$	
				$\hat{Y}_{TOC}^* = 23.23 + 0.2052x - 0.0036x^2, R^2 = 0.9859$	

Means followed by the same letter in columns by source of variation do not differ significantly at 5% probability by the Tukey's test. ns: not significant values; * and **: values significant at $P < 0.05$ and $P < 0.01$, respectively

Table 2. Seedlings of tree species introduced in the experimental area and percentage of survival (Survival) after 36 months.

Tabla 2. Plántulas de especies arbóreas introducidas en la zona experimental y porcentaje de supervivencia (Survival) luego de 36 meses.

Family	Scientific name	Popular name	Survival (%)
Anacardiaceae	<i>Astronium fraxinifolium</i> Schott	Gonçalo Alves	97
Annonaceae	<i>Xylopia aromatica</i> Lam. (Mart.)	Pimenta de Macaco	87
Apocynaceae	<i>Hancornia speciosa</i> Gom.	Mangaba	91
Bignoniaceae	<i>Tabebuia caraiba</i> Mart.	Ipê Amarelo	96
Euphorbiaceae	<i>Mabea fistulifera</i> Mart.	Canudo de Pito	81
Fabaceae	<i>Acacia polyphylla</i> DC.	Monjoleiro	79
	<i>Anadenanthera falcata</i> (Benth.) Speg.	Angico do Cerrado	89
	<i>Dipteryx alata</i> Vogel	Baru	90
	<i>Hymenaea stigonocarpa</i> Mart.	Jatobá do Cerrado	97
Myrtaceae	<i>Psidium guineense</i> Swartz	Araçá do Campo	95

remained under fallow for three months. In February 2012, seedlings of tree species common in the Cerrado of the region (Table 2) were planted in holes (0.40 m deep) spaced at 4 m x 5 m, comprising 1080 seedlings, and distributed to include three individuals of each species per treatment, per repetition.

The spacing (4 m x 5 m) was intended to allow other species to establish themselves. The seedlings were at least 0.30 m high at the time of planting (Figure 2). Twelve months after the start of the recovery process, an

evaluation of the spontaneous vegetation was conducted, with a census (100%) of the individuals present in the experimental area (Mantovani et al. 2005), without considering the introduced seedlings. The individuals of the herbaceous stratum, including grasses, herbs and creepers, were also identified.

A second evaluation was carried out 36 months after the start of the recovery process in the experimental plots (20 m x 30 m) with the recovery treatments, when all individuals from the shrub-arboreal layer higher than 30

cm were identified, except for the introduced seedlings. However, all individuals from the herbaceous layer, including grasses and creepers, were identified in subplots of 5 x 5 m, located in the upper left corner of the plots (Munhoz and Araújo 2011), due to the number of individuals in this second evaluation (36 months) it was necessary to work in subplots.

The plants were identified in the field, but when this was not possible, the botanical material was collected, photographed and later identified at the plant family level, following the classification system the angiosperm phylogeny group-APG VI (Chase et al. 2016). To geographic origin of species was defined as native or alien based on the available literature (Silva Júnior 2005; Neto et al. 2010; Barbosa 2017; Flora do Brasil 2018) and the dispersal syndromes were determined according to the van der Pijl (1982) classification, which divides the species into three groups: 1) anemochory - dispersal by wind; 2) autochory - self-dispersal or dispersal without the action of a dispersing agent, and 3) zoochory - dispersal by animals, (Oliveira et al. 2014; Barbosa 2017; Flora do Brasil 2018). At this time, 36 months after the start of the recovery process, the introduced seedlings were quantified to evaluate their overall survival, and the bare subsoil under recovery process was analyzed for bulk density, and total organic carbon at a depth of 0.0-0.2 m, with three repetitions, as described previously. These data and vegetation data were subjected to analysis of variance (ANOVA) using the design and scheme described above. When a significant difference was found between treatments, they were compared using the Tukey test ($P < 0.05$). The vegetation was also compared in numerical terms.

RESULTS

The effects of mechanization and residues (MAC and BCR) on soil bulk density (BD) and total organic carbon (TOC) were evident. There was a reduction in BD from 1.66 Mg/m³ before intervention (Table 1) to 1.35 Mg/m³ with 32 t/ha of MAC or 30 t/ha of BCR, and the levels of TOC increased slightly in response to increasing doses of MAC and BCR (Table 1). The reduction in BD and the increase in TOC content indicate that positive edaphic changes have occurred with mechanization and the residue introduction. Although BD and TOC did not reach values similar to those observed in CCER, they initiated a recovery process of

the vegetation cover with a predominance of Cerrado species.

After 36 months of experimentation, all 10 introduced species were present in the experimental area, with only minor differences in survival rates. This suggests a good ability to adapt to the new subsoil environment. *Hancornia speciosa* Gom, *Psidium guineense* Swartz, *Tabebuia caraiba* Mart and *Astronium fraxinifolium* Schott, showed survival rates between 90% and 97%; *Mabea fistulifera* Mart, *Xylopia aromatica* Lam. (Mart.), *Dipteryx alata* Vogel and *Anadenanthera falcata* (Benth.) Speg, between 81% and 90%, and *Acacia polyphylla* DC, a survival rate of 79% (Table 2). These results indicate that these species could be successful in revegetating heavily impacted areas, such as those under study.

After 12 months of experimentation, we recorded 73 species in the area, comprising 64 natives and 9 aliens. These species belong to 24 families, with the predominance of Fabaceae, Euphorbiaceae, Poaceae and Malvaceae, with 19, 6, 6 and 5 species, respectively (Table 3). Among the species identified, 20 were shrubs or trees and nine were no-native herbs, most of which (5 species) were from the Poaceae family.

The floristic survey after 36 months revealed 72 species from 27 families (Table 3), dominated by Fabaceae (16 species), Poaceae (8), Asteraceae (6) and Euphorbiaceae (5) (Figure 3). The number of shrubs and tree species increased to 25. The 7 alien species identified were all herbaceous and belonged to 4 families: Poaceae (four species), Amaranthaceae (one), Commelinaceae (one) and Fabaceae (one). Several species colonized the degraded area after the interventions, including those that were planted as part of the recovery process and those that emerged spontaneously. Some of these species were already flowering or producing fruit after 36 months.

From 12 to 36 months, the number of plant families increased from 24 to 27 (Table 3). Seven new families emerged (Anacardiaceae, Bignoniaceae, Clusiaceae, Connaraceae, Ebenaceae, Moraceae and Salicaceae), while 4 families that were present at 12 months were not recorded at 36 months (Cucurbitaceae, Nyctaginaceae, Phyllanthaceae and Verbenaceae). It is important to note that the first evaluation (at 12 months) was a census of the entire area, while the second evaluation (at 36 months) was carried out on a sub-plot.

Table 3. Spontaneous plant species identified at the experimental area with 12 and 36 months of experimentation, family, stratum (herbaceous-H, shrub-arboreal-S), origin (alien-A, native-N) and dispersal syndrome (anemochory-ANE, autochory-AUT and zoochory-ZOO).

Tabla 3. Especies vegetales espontáneas identificadas en el área experimental con 12 y 36 meses de experimentación, familia, estrato (herbáceo-H, arbustivo-arbóreo-S), origen (exótico-A, nativo-N) y síndrome de dispersión (anemocoria-ANE, autocoria-AUT y zoocoria-ZOO).

Family/ Scientific Name	Stratum	Origin	Dispersion	12 months	36 months
Amaranthaceae					
<i>Amaranthus deflexus</i> L.	H	A	ANE	x	
<i>Gomphrena celosioides</i> Mart.	H	A	AUT	x	x
Anacardiaceae					
<i>Astronium fraxinifolium</i> Schott	S	N	AUT		x
Annonaceae					
<i>Annona coriacea</i> Mart.	S	N	ZOO		x
<i>Annona dioica</i> A. St. -Hil.	S	N	ZOO	x	x
<i>Annona phaeoclados</i> Mart.	S	N	ZOO	x	x
Apocynaceae					
<i>Barjonia cymosa</i> E. Fourn.	H	N	WC [‡]	x	
<i>Blepharodon bicuspidatum</i> E. Fourn.	H	N	ANE	x	x
<i>Himatanthus obovatus</i> (Müll. Arg.) Woodson	S	N	ANE	x	x
Asteraceae (Compositae)					
<i>Acanthospermum australe</i> (Loefl.) Kuntze	H	N	ZOO	x	x
<i>Conyza bonariensis</i> (L.) Cronquist	H	N	ANE		x
<i>Eclipta alba</i> (L.) Hassk.	H	N	ANE		x
<i>Piptocarpha rotundifolia</i> (Less.) Baker	H	N	ANE		x
<i>Porophyllum ruderale</i> (Jacq.) Cass.	H	N	ANE	x	x
<i>Synedrellopsis grisebachii</i> Hieron. and Kuntze	H	N	WC [‡]	x	
<i>Vernonia scabra</i> Pers.	H	N	ANE		x
Bignoniaceae					
<i>Anemopaegma arvense</i> (Vell.) Stellfeld ex De Souza	H	N	ANE		x
Clusiaceae					
<i>Garcinia brasiliensis</i> Mart.	S	N	ZOO		x
Commelinaceae					
<i>Commelina benghalensis</i> L.	H	A	AUT	x	x
Connaraceae					
<i>Comarus suberosus</i> Planch.	S	N	ZOO		x
Convolvulaceae					
<i>Ipomoea cairica</i> (L.) Sweet	H	N	AUT	x	x
<i>Ipomoea purpurea</i> (L.) Roth.	H	N	AUT		x
<i>Ipomoea ramosissima</i> (Poir.) Choisy	H	N	AUT	x	
<i>Merremia umbellata</i> (L.) Hallier F.	H	N	AUT	x	
Cucurbitaceae					
<i>Citrullus lanatus</i> (Thunb.) Matsum. and Nakai	H	N	AUT	x	
Cyperaceae					
<i>Bulbostylis paradoxa</i> (Spreng.) Lindm.	H	N	ANE	x	x
<i>Cyperus meyenianus</i> Kunth	H	N	AUT	x	x
Dilleniaceae					
<i>Curatella americana</i> L.	S	N	ZOO	x	x
<i>Davilla elliptica</i>	S	N	ZOO		x
Ebenaceae					
<i>Diospyros hispida</i> A. DC.	S	N	ZOO		x
Euphorbiaceae					
<i>Cnidoscolus albomaculatus</i> (Pax) I. M. Johnst.	S	N	AUT	x	
<i>Croton glandulosus</i> L.	S	N	AUT	x	x
<i>Euphorbia hyssopifolia</i> L.	H	N	AUT	x	x
<i>Euphorbia hirta</i> L.	S	N	AUT	x	
<i>Jatropha elliptica</i> (Pohl) Oken	S	N	AUT	x	
<i>Mabea fistulifera</i> Mart	S	N	ZOO		x
<i>Manihot tripartita</i> (Spreng.) Müll. Arg.	H	N	ZOO	x	x
<i>Sebastiania hintonii</i> Lundell	S	N	AUT		x
Fabaceae (Leguminosae)					
<i>Acosmium dasycarpum</i> (Vogel) Yakovlev	S	N	ANE	x	x
<i>Acosmium subelegans</i> (Mohlenbr.) Yakovlev	S	N	ANE	x	x
<i>Aeschynomene histrix</i> Poir.	H	N	ZOO	x	x
<i>Aeschynomene paniculata</i> Vogel	H	N	ZOO	x	x
<i>Alysicarpus vaginalis</i> (L.) DC.	H	A	AUT	x	x
<i>Bauhinia curvula</i> Benth	S	N	AUT		x
<i>Bowdichia virgilioides</i> Kunth	S	N	ANE	x	x
<i>Chamaecrista desvauxii</i> (Collad.) Killip	H	N	AUT	x	x
<i>Chamaecrista flexuosa</i> (L.) Greene	H	N	AUT		x
<i>Chamaecrista nictitans</i> (L.) Moench	H	N	AUT	x	

Table 3. Continuation

Tabla 3. Continuación

<i>Chamaecrista serpens</i> (L.) Greene	H	N	AUT	x	
<i>Desmodium incanum</i> DC.	H	N	ZOO	x	x
<i>Galactia eriosematoides</i> Harms	H	N	AUT	x	
<i>Macropitium prostratum</i> (Benth) Urb.	H	N	AUT		x
<i>Mimosa adenocarpa</i> Benth	H	N	AUT		x
<i>Mimosa nuda</i> Benth.	H	N	AUT	x	
<i>Mimosa pigra</i> L.	S	N	AUT	x	
<i>Mimosa quadrivalvis</i> L.	H	N	AUT	x	
<i>Senna obtusifolia</i> (L.) H. S. Irwin and Barneby	H	N	AUT	x	
<i>Senna occidentalis</i> (L.) Link	H	N	AUT	x	
<i>Stylosanthes acuminata</i> M.B.Ferreira and Sousa Costa	H	N	AUT		x
<i>Stylosanthes guianensis</i> (Aubl.) Sw.	H	N	AUT	x	
<i>Stylosanthes leiocarpa</i> Vogel	H	N	AUT		x
<i>Stylosantes viscosa</i> (L.) Sw.	H	N	AUT	x	x
<i>Zornia reticulata</i> Sm.	H	N	ZOO	x	x
Lamiaceae					
<i>Aegiphila verticillata</i> Vell.	S	N	ZOO	x	x
Malpighiaceae					
<i>Byrsonima intermedia</i> A. Juss.	S	N	ZOO	x	x
<i>Byrsonima verbascifolia</i> (L.) Rich. ex Juss.	S	N	ZOO	x	x
<i>Camarea hirsuta</i> A. St. -Hil.	S	N	WC ^f	x	x
Malvaceae					
<i>Sida cerradoensis</i> Krap.	H	N	AUT	x	x
<i>Sida linifolia</i> Juss. ex Cav.	H	N	AUT	x	x
<i>Sida rhombifolia</i> L.	H	N	AUT	x	
<i>Waltheria communis</i> A. St. -Hil.	H	N	AUT	x	
<i>Waltheria indica</i> L.	H	N	AUT	x	x
Moraceae					
<i>Brosimum gaudichaudii</i>	S	N	ZOO		x
Nictaginaceae					
<i>Boerhavia diffusa</i> L.	H	N	AUT	x	
Passifloraceae					
<i>Piriqueta corumbensis</i> Moura	H	N	AUT		x
<i>Piriqueta rosea</i> (A. St. -Hil., A. Juss. and Cambess.) Urb.	H	N	AUT	x	x
<i>Turnera melochioides</i> A. St. -Hil. and Cambess.	H	N	AUT	x	
Phyllanthaceae					
<i>Phyllanthus tenellus</i> Roxb.	H	N	AUT	x	
Poaceae					
<i>Andropogon bicornis</i> L.	H	N	ANE	x	x
<i>Aristida gibbosa</i> (Nees) Kunth	H	N	ANE		x
<i>Aristida riparia</i> Trin.	H	N	ANE		x
<i>Digitaria ciliaris</i> (Retz.) Koeler	H	A	AUT	x	
<i>Digitaria insularis</i> (L.) Mez ex Ekman	H	A	AUT	x	
<i>Hyparrhenia rufa</i> (Ness) Stapf.	H	A	AUT		x
Indeterminada 1	H	-	-		x
<i>Panicum maximum</i> L.	H	A	ANE		x
<i>Rhynchelytrum repens</i> (Willd) C. E. Hubb.	H	A	ANE	x	x
<i>Urochloa decumbens</i> Stapf	H	A	ANE	x	x
<i>Urochloa mutica</i> (Forssk.) Stapf	H	A	AUT	x	
Polygalaceae					
<i>Polygala violacea</i> Aubl.	H	N	AUT	x	
Portulacaceae					
<i>Portulaca oleracea</i> L.	H	N	ANE	x	
Rubiaceae					
<i>Alibertia edulis</i> (Rich.) A.Rich. ex DC.	S	N	ZOO	x	
<i>Diodella teres</i> (Walter) Small	H	N	AUT	x	
<i>Richardia grandiflora</i> (Cham. and Schltld.) Steud.	H	N	AUT	x	x
<i>Spermacoce latifolia</i> Aubl.	H	N	ZOO	x	x
Salicaceae					
<i>Casearia sylvestris</i> Sw.	S	N	ZOO		x
Sapindaceae					
<i>Magonia pubescens</i> A. St. -Hil.	S	N	ZOO		x
<i>Serjania lethalis</i> A. St. -Hil.	H	N	ANE	x	x
Solanaceae					
<i>Solanum lycocarpum</i> A. St.-Hil.	S	N	ZOO	x	x
<i>Solanum sisymbriifolium</i> Lam.	S	N	ZOO	x	
Verbenaceae					
<i>Stachytarpheta cayennensis</i> (Rich.) Vahl	H	N	AUT	x	
Vochysiaceae					
<i>Qualea parviflora</i> Mart.	S	N	ANE	x	x

This may have created the impression that some species disappeared. Among the families present at both evaluations (Table 3), Asteraceae, Euphorbiaceae, Fabaceae and Poaceae showed variations in species composition between 12 and 36 months. Of the seven species recorded at 36 months that belonged to seven new families, five were either shrubs or trees and two were herbs. This indicates the spontaneous emergence of shrub and tree species in the area and suggests progress in the recovery process.

After 36 months, the treatment involving only mechanization resulted in the presence

of 5 species across three families (Table 4). In contrast, treatments with the addition of MAC and BCR significantly increased richness. The average number of families almost tripled, and the number of species exceeded 15 when 32 t/ha of MAC was applied, either alone or in combination with 15 or 30 t/ha of BCR. This highlights the effectiveness of the 32 t/ha MAC application, regardless of the presence of BCR (Table 4). In relation to dispersal syndromes, 45% (16 species) of the regenerating shrub species identified after 12 months were zoochorous. After 36 months, this proportion increased to 56% (24 species) (Figure 4, Table

Table 4. Average of different families (FAM), species (NSPEC), native (NAT) and aliens (Aliens) species, according to the treatments (doses of macrophytes [MAC] and biochar [BCR]), by doses of macrophytes (MAC) and biochar (BCR).

Tabla 4. Promedios de diferentes familias (FAM), especies (NSPEC), especies nativas (NAT) y exóticas (Aliens), según los tratamientos (dosis de macrófitas [MAC] y biocarbón [BCR]), por dosis de macrófitas (MAC) y biocarbón (BCR).

MAC (t/ha)	BCR (t/ha)	FAM	NSPEC	NAT	Aliens
0	0	3	5	4	1
0	15	8	13	12	1
0	30	8	12	11	2
0	45	6	10	8	3
16	0	8	14	13	1
16	15	7	12	10	3
16	30	8	14	13	3
16	45	9	14	10	6
32	0	10	16	14	3
32	15	10	17	16	1
32	30	13	18	5	5
32	45	10	15	13	5

Tukey test (P>0.05)

Table 5. F Values for number of families (FAM), of species (NSPEC), of native (NAT) and alien (Alien) species, of autochory (AUT), anemochory (ANEM) and zoochory (ZOOC), coefficient of variation (CV) and average after 36 months of intervention.

Tabla 5. Valores F para el número de familias (FAM), de especies (NSPEC), de especies nativas (NAT) y exóticas (Alien), de autocoria (AUT), anemocoria (ANEM) y zoocoria (ZOOC), coeficiente de variación (CV) y promedio tras 36 meses de intervención.

Source of variation	FAM	NSPEC	NAT	Aliens	AUT	ANEM	ZOOC
MAC	0.0152*	5.754**	0.3381 ^{ns}	0.0165*	4.890*	1.945 ^{ns}	1.781 ^{ns}
BCR	0.5595 ^{ns}	1.024 ^{ns}	0.6130 ^{ns}	0.0000**	0.495 ^{ns}	1.445 ^{ns}	0.838 ^{ns}
MAC x BCR	0.6909 ^{ns}	1.280 ^{ns}	0.1131 ^{ns}	0.0752 ^{ns}	0.570 ^{ns}	2.201 ^{ns}	2.681*
CV (%)	41	18	48	44	25	19	26
Average	8.3	3.7	10.7	1.7	2.4	2.0	2.0
MAC							
0	6.4b	10.3B	8.9a	1.2b	3.9b	3.0a	3.2a
16	7.8ab	13.3AB	11.3a	1.8ab	5.7ab	3.8a	3.9a
32	10.8a	16.7A	11.9a	2.1a	7.4a	4.2a	4.7a
BCR							
0	7.1	11.6	10.4	1.1	5.1	3.1	3.2
15	8.4	14.1	12.7	1.1	5.4	3.8	4.2
30	9.4	14.8	9.6	1.6	5.9	4.4	4.4
45	8.3	13.2	10.2	2.9	6.2	3.2	3.8
	\hat{Y}_{FAM}^{ns}	\hat{Y}_{NSPEC}^{ns}	\hat{Y}_{NAT}^{ns}	#	\hat{Y}_{AUT}^{ns}	\hat{Y}_{ANEM}^{ns}	\hat{Y}_{ZOOC}^{ns}

= Eq_(Alien) 0.8 + 0.0385x; R²: 0.7860, P: 0.0001

Means followed by the same letter in columns by source of variation do not differ significantly at 5% probability by the Tukey's test. ns: not significant values; * and **: values significant at P<0.05 and P<0.01, respectively

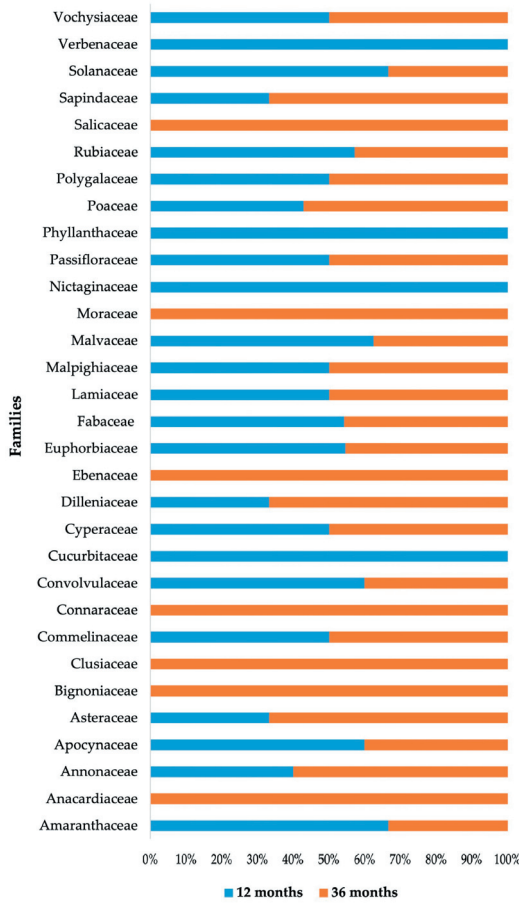


Figure 3. Distribution of spontaneous species in families.

Figura 3. Distribución de las especies espontáneas en familias.

5), suggesting an important contribution of fauna to the reintroduction of this stratum.

The species *Aristida riparia* and *Waltheria indica* – both native to the Cerrado – were the most frequent, occurring in eight treatments each and present in all three experimental plots. *Hyparrhenia rufa*, an exotic species, was found in seven treatments, while *Stylosanthes acuminata* – a species native to the Cerrado – was found in six treatments. The treatment with 32 t/ha MAC + 45 t/ha BCR contained four of the aforementioned species across the three experimental plots.

The native species *Aristida riparia*, *Waltheria indica*, *Zornia reticulata*, *Stylosanthes acuminata* and the alien species *Hyparrhenia rufa* were found in at least one plot across the twelve treatments. These five species are the most common in the experimental area. In contrast, there were 23 species that were found in only one plot of a single treatment. Among these, nine species exhibit zoochorous dispersal, indicating the presence of dispersal agents in the area.

DISCUSSION

The bare subsoil without any intervention (BSWI) had a bulk density of 1.66 Mg/m³ at a depth of 0.0-0.2 m (Table 1). This high bulk density hinders soil water infiltration (Liao et al. 2023). Poor soil water recharge results

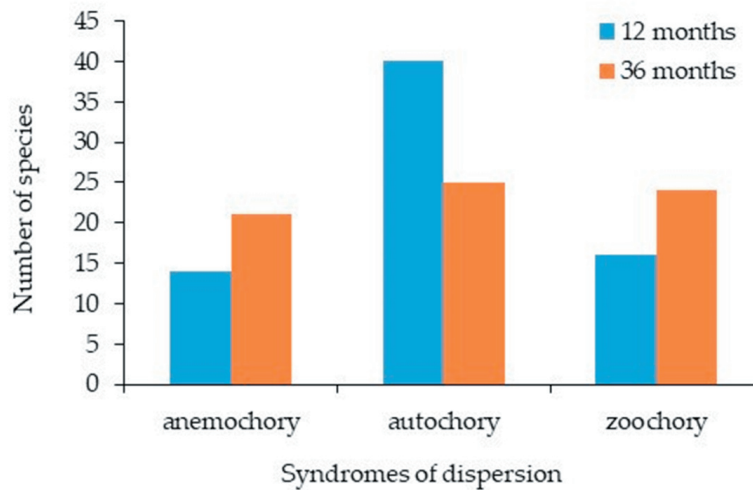


Figure 4. Syndromes of dispersal of spontaneous species in the experimental area, with 12 and 36 months of experimentation.

Figura 4. Síndromes de dispersión de especies espontáneas en la zona experimental, con 12 y 36 meses de experimentación.

in water stress and helps to explain the low vegetation density —or even the complete absence of vegetation cover— as well as the difficulty plants face in establishing and maintaining themselves (Niang et al. 2015).

Revegetation of degraded areas changes soil physicochemical properties, including bulk density, porosity, organic matter and moisture (Deng et al. 2016; Yi et al. 2021). However, bulk density exceeding 1.55 Mg/m³ was considered restrictive to vegetation growth, inhibiting root system development and water infiltration (Kiehl 1979; Kozłowski 1999). In CCER, the average density was 1.23 Mg/m³ (Table 1). Thus, the mechanization and the incorporation of MAC and BCR were effective. After 36 months, the average bulk density was 1.35 Mg/m³ (Table 1), a value that no longer limits root growth and can improve water infiltration.

Soil organic carbon is also important for maintaining vegetation cover, as it contributes to moisture retention, participates in the biogeochemical cycle of various elements essential for plant nutrition and provides many other benefits (FAO 2017). In this case, the average TOC increased from 22.8 mg/g in BSWI to 25.0 mg/g after 36 months, but it remained low compared to the 35.0 mg/g observed in CCER. Although the gains in both BD and TOC were modest, the presence of vegetation covering the area is already visible (Figure 2e). This allows us to infer that both mechanization and the addition of MAC and BCR are still contributing to the re-establishment of vegetation cover. The expectation is that after 36 months, the vegetation will become established and effectively cover the surface, thereby reducing erosion and creating better soil conditions.

The introduction of MAC and BCR, the mechanization of the degraded area, and the planting of seedlings have all contributed to improving the edaphic conditions. This has facilitated the initial re-establishment of vegetation cover, composed mainly of native Cerrado species, although some exotic species are also present.

The occurrence of alien species was low at both 12 and 36 months, and they were most common among the Poaceae. The fact that few alien species occur in each area does not necessarily mean that their impact is less significant (Dechoum et al. 2021). Some alien species can be highly competitive within

certain ecosystems (Martins et al. 2017). For example, African grasses such as Gamba grass (*Andropogon gayanus*), Brachiaria (*Urochloa* spp.) and Jaragua grass (*Hyparrhenia rufa*) are highly competitive in the Cerrado savanna (Martins et al. 2017). Brachiaria and Jaragua grass are present in the study area, so it is necessary to monitor their spread. Invasive alien species have been identified as one of the main threats to species extinction (Dechoum et al. 2021; Pouteau et al. 2023).

The family with the highest frequency at both 12 and 36 months was Fabaceae, which, according to Chase et al. (2016), is one of the botanical families with the largest number of species and occurs in regions with seasonally dry or arid climates. Several authors have reported that this family contributed the most to the species richness in the shrub-arboreal stratum of the Brazilian savannas (Eiten 1972; Ratter et al. 2001; Costa et al. 2004). The presence of Fabaceae can facilitate the establishment of other species (Meira-Neto et al. 2017), especially in extreme climatic situations (Khan et al. 2014), due to its ability to fix nitrogen through nodulation (Meira-Neto et al. 2017), its efficiency in obtaining potassium, calcium and magnesium (McLean et al. 1956), among others. These findings indicate that vegetation cover increased in the area where mechanization and the introduction of MAC and BCR took place, with emphasis on the 32 t/ha MAC treatment. The dominance of Fabaceae in the area can be attributed to several factors. Firstly, the area is located in the central region of Brazil, which is characterized by seasonal climate changes and periods of water restriction (Lima et al. 2015). This region is recognized as a principal center for the diversification of the Fabaceae family (Polhill and Raven 1981). In addition, species within this family exhibit greater ecological plasticity, enabling them to inhabit adverse environments (Jesus et al. 2016).

Interestingly, some species present at 12 months were not recorded at 36 months, while others colonized the area during this period. According to Ratter et al. (2003), this can be explained by natural variation between evaluations. Additionally, this may be because the experimental area was still undergoing recovery and had not yet stabilized (Figure 3). For degraded areas under conditions similar to those described here, Costa and Alves (2016) observed the presence of only three species after 15 years of rehabilitation. Durigan et al. (2004) evaluated regenerating individuals in

areas undergoing recovery and found that 53% and 74% of the individuals (in two different areas) were concentrated in just two species, highlighting the low diversity resulting from the restoration treatments. In this study, we recorded 72 species after 36 months (three years) of recovery. This species richness is greater than that reported by Costa and Alves (2016) after 15 years in a similarly degraded area, suggesting that the results obtained so far indicate a positive trajectory for the recovery process.

Of the 72 species recorded at 36 months, 25 were either shrubs or trees. Thirteen of these shrub and tree species — *Acosmium dasycarpum*, *Annona coriacea*, *Astronium fraxinifolium*, *Bowdichia virgilioides*, *Brosimum gaudichaudii*, *Byrsonima verbascifolia*, *Casearia sylvestris*, *Curatella americana*, *Davilla elliptica*, *Diospyros hispida*, *Mabea fistulifera*, *Magonia pubescens* and *Solanum lycocarpum*— were also recorded by Calgaro et al. (2015) in a nearby degraded area. The presence of five species from three families in the mechanization-only treatment indicates that mechanization alone also helped to re-establish vegetation cover. In treatments where MAC and BCR were added, the number of families doubled and species richness exceeded 30 when 32 t/ha of MAC was applied, either alone or in combination with 15 or 30 t/ha of BCR. This highlights the importance of adding organic material for the recovery of vegetation cover.

Fauna that disperses seeds and fruits promotes the entry of new plant species from neighboring fragments, helping to spread their seeds and contributing to the colonization of the area under recovery. This process increases local species richness (Pilon and Durigan 2013) and contributes to revegetation, especially since there was no clear potential for regrowth in the area prior to intervention. Zoochorous dispersal occurred only after soil preparation and the introduction of residues and seedlings. These actions created niches that facilitated fauna visits and subsequent seed deposition, highlighting zoochorous dispersal as an important contributor to the recovery of shrubs and trees on the bare subsoil.

Vieira et al. (2002) reported that 26.7% of species they found in the Cerrado sensu stricto were anemochorous, indicating their importance in open areas. In our study, after 36 months, 29% of the species were anemochorous. This confirms the importance of mechanization and the introduction of MAC and BCR: by turning over the surface layer,

these interventions reduced soil density and improved TOC levels, promoting conditions for the establishment of anemochorous species in the recovering area. This also emphasizes the importance of nearby Cerrado fragments, which Ferreira et al. (2010) cited as fundamental to the recovery process of degraded areas, especially in the absence of storage organs.

It is important to reiterate the significance of the recovery process, which began with the mechanization of the bare subsoil and the incorporation of residues, and subsequently enabled autochorous and anemochorous dispersal. The disruption of the surface layer, the incorporation of organic material, and the introduction of seedlings at wide spacing (4 m x 5 m) were essential for improving edaphic conditions, allowing new species to colonize the area and initiate a long-term recovery process. After 36 months, the number of autochorous species (25) was similar to the number of zoochorous (24) and anemochorous (21) species, indicating a balance among dispersal modes. However, at 12 months, autochorous species predominated, suggesting that environmental conditions (e.g., soil conditions, surrounding vegetation, available fauna) were not yet conducive to the establishment of zoochorous or anemochorous species. This can be explained by the completely open environmental conditions of the studied area. In the savanna and campestre formations of the Cerrado, where herbaceous species predominate, the modes of dispersal are simpler, and plants that require lower energy costs, such as those with passive autochory, are favored (Kuhlmann and Ribeiro 2016).

Prior to the start of the recovery process in November 2011, the experimental site was bare subsoil (Figure 2a). In addition to the lack of vegetation cover, the surface had been deeply compacted, which hindered water infiltration and contributed, via surface runoff, to the removal of any seeds that had arrived. According to the surveys conducted at 12 and 36 months, the applied techniques produced positive results, including an increase in plant richness and the presence of trees, shrubs and grasses, all of which are important components of Cerrado vegetation (Pellizzaro et al. 2017).

CONCLUSIONS

This study showed that a combination of active surface management and organic residue incorporation effectively overcame

the key limitations to recovering bare subsoil areas in the Cerrado. These interventions not only increased species richness but also reactivated essential ecological processes, such as colonization and dispersal. This led to rapid vegetation establishment within 36 months. The dominance of native and animal-dispersed species highlights the importance of surrounding vegetation and landscape connectivity for restoration success. From an applied perspective, the consistent positive

effect of aquatic macrophytes, regardless of biochar addition, provides a simple, scalable and cost-effective strategy for initiating biodiversity recovery in severely degraded subsoils associated with large-scale disturbances.

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