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REVEGETATION OF AREAS DEGRADED BY MINING IN THE CERRADO: THE USE OF SEWAGE SLUDGE IN SOIL REHABILITATION[1]

REVEGETAÇÃO DE ÁREAS DEGRADADAS PELA MINERAÇÃO NO CERRADO: O USO DO LODO DE ESGOTO NA REABILITAÇÃO DO SOLO

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ABSTRACT

Among the activities that negatively impact areas of the Brazilian Cerrado biome, mining is one of the most significant for the country's economy, representing around 8% of its Gross Domestic Product (GDP). However, mining causes serious environmental damage, requiring chemical, physical and biological rehabilitation of the exposed substrate to start ecosystem recolonization. Mine rehabilitation for revegetation requires adding large amounts of organic matter to exposed substrates. Studies on using domestic sewage sludge as an organic matter and nutrient source for plants have yielded significant results in ecological restoration protocols. This article presents a traditional narrative review of the literature related to the ecological, chemical, and physical processes in the application of sewage sludge for rehabilitating mining substrates in the Cerrado. It analyzed 95 articles, from 1985 to 2023, across 72 scientific journals. The results show that applying sewage sludge at rates bellow 100 t ha-1 (dry basis) raised soil pH and iron concentration, stabilized carbon, increased water availability, and decreased invasive plant recruitment. Additional techniques include sowing plants with functional characteristics similar to those of invasive species, increasing the functional diversity of species in plant communities, and identifying and manipulating ecological filters to stimulate the recruitment of native plant species. Soil-plant feedbacks determine crucial points for ecosystem balance and regulate available resources. Treatment with sewage sludge at rates bellow < 100 t ha-1 (dry basis) optimized the physical, chemical, and biological characteristics of exposed substrates, accelerating the colonization of plant communities and demonstrating the need for continuous monitoring of interactions between the edaphic environment and plants to establish biological diversity.

Keywords: biosolids; ecological filters; invasive species; soil-plant interactions; soil recomposition.

RESUMO

A mineração representa aproximadamente 8% do Produto Interno Bruto (PIB) nacional e é uma das principais causas de degradação no bioma Cerrado no Brasil. Essa retirada do solo exige reabilitação química, física e biológica do substrato exposto para iniciar a recolonização do ecossistema. Para a revegetação, é necessário adicionar grandes quantidades de matéria orgânica aos substratos expostos. Estudos com lodo de esgoto doméstico como fonte de matéria orgânica e nutrientes para plantas têm resultados promissores em protocolos de restauração ecológica. Este artigo apresenta uma revisão narrativa tradicional da literatura relacionada aos processos ecológicos, químicos e físicos na aplicação de lodo de esgoto para reabilitar substratos de mineração no Cerrado. Foram revisados 95 artigos, de 1985 a 2023, em 72 revistas científicas. A aplicação de lodo de

1 Bibliographic Review Article

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esgoto em taxas inferiores a 100 t ha-1 (base seca) elevou o pH do solo e a concentração de ferro, estabilizou o carbono, aumentou a disponibilidade de água e reduziu o recrutamento de plantas invasoras. Outras técnicas incluem a semeadura de plantas com características semelhantes às de espécies invasoras, aumento da diversidade funcional de espécies em comunidades vegetais e identificação e manipulação de filtros ecológicos para estimular o recrutamento de espécies nativas. Os feedbacks solo-planta desempenham um papel crucial na regulação dos recursos disponíveis. O tratamento adequado com lodo de esgoto otimiza características físicas, químicas e biológicas dos substratos expostos, acelerando a colonização das comunidades vegetais e enfatizando a necessidade de monitoramento contínuo das interações solo-planta para restaurar a diversidade biológica.

Palavras-chave: *biossólidos; espécies invasoras; filtros ecológicos; interações solo-planta; recomposição do solo.*

INTRODUCTION

The Cerrado biome is a mosaic of plant physiognomies that include grassland, savanna and forest formations (DANTAS *et al*., 2013). Among the terrestrial biomes, it is the one that houses the highest degree of endemism and species diversity, though it is one of the most threatened biome in South America, since half of Cerrado's native cover has been removed for agricultural, urban and mining activities, which lead to high fragmentation of habitats (COLLI *et al*., 2020). Only 20% of the original Cerrado cover remains intact and only 2.2% of its original area of occurrence is located in protected areas (FERREIRA *et al*., 2020). Despite being the second largest biome in Brazil, the Cerrado is in a critical situation, as significant environmental degradation threatens the existence of several animal and plant species. Such a situation compromises ecological processes involved in the maintenance of Cerrado's ecosystems and dynamics associated with environmental services.

One of the greatest threats to Cerrado diversity is the presence of invasive alien species, which impact native protected areas and represent the second strongest cause of worldwide biodiversity loss (SAMPAIO; SCHMIDT, 2013). Invasive exotic plant species usually produce a large number of small seeds that have anemochoric dispersion and have high longevity in the soil, grow rapidly with early maturation, additionally reproduce themselves by budding, long flowering and fruiting, have pioneering behavior, adapt to degraded and open areas, are reproductively efficiency, and release toxins that prevent the growth of neighboring plants (allelopathy) (FRANCO, 2013). The establishment of trees in degraded sites in many tropical areas is challenging due to invasive plants and competition with weeds (STARR *et al*., 2013), as well as edaphic limiting factors. Therefore, research on cultivating native species capable of inducing the rehabilitation of chemical, physical, and biological characteristics of soils and substrates is crucial for ecological restoration and the control of exotic species. The objective of this review is to unveil which ecological, chemical, and physical aspects are relevant to the rehabilitation of mining substrates treated with sewage sludge in the Brazilian Cerrado, aiming at ecosystem restoration.

DEVELOPMENT

REVIEW METHODS

This article presents a traditional narrative review of the literature related to the ecological, chemical, and physical processes involved in the application of sewage sludge to rehabilitate mining substrates in the Cerrado region of Brazil. We examined 95 articles from 72 journals from Google Scholar and Scielo databases, covering the period from 1985 to 2023. The aim was to assess the state of scientific knowledge on monitoring the ecological processes involved in the rehabilitation or restoration of areas degraded by mining that employed sewage sludge as a source of organic matter and plant nutrients.

Among the documents, articles from 72 peer-reviewed journals that are widely recognized and frequently cited in the scientific literature were consulted. The traditional narrative literature review allows for a broad description of the subject but does not exhaust all sources of information, as it is not conducted through systematic search and data analysis. Its importance lies in the broad and rapid updating of studies on the subject.

The descriptors "areas degraded by mining," "sewage sludge"," "recovery of mined areas in the Cerrado," "use of sewage sludge in the Cerrado," "sewage sludge in mined areas," "ecology of sewage sludge," and "recovery of soils degraded by mining in the Cerrado" were inserted in Google Scholar and Scielo databases. Studies that presented ecological aspects related to the use of sewage sludge in mined areas of the Cerrado and studies on ecological processes associated with the recovery of soil degraded by mining in the Cerrado were selected.The selection of articles was according to the objective of the review, which was to determine which ecological, physical, chemical, and biological aspects are relevant in the rehabilitation of mined substrates treated with sewage sludge in the Cerrado biome, to characterize the research object broadly. Ninety-five bibliographic sources relevant to the objective of this review were identified and included. Articles on the rehabilitation of degraded areas caused by other activities than mining and not related to the Cerrado biome were excluded. Rother (2007) and Botelho *et al.* (2011) and refer to traditional literature review articles as "narrative review" articles, characterized as publications that aim to describe, in a broad manner, the development of a specific subject and the types of methodologies being used by academics and researchers to study the topic. Botelho *et al.* (2011) state that "the narrative review is used to describe the state of the art of a specific subject, from a theoretical or contextual point of view". The topics of this review were divided into Introduction; Development and Conclusions. The "Development" section has been divided into Review Methods, Rehabilitation of Areas Degraded by Mining in the Cerrado Biome, Sewage Sludge Treatment of Exploited Mines, and Recovery of Degraded Areas and Associated Ecological Processes.

REHABILITATION OF AREAS DEGRADED BY MINING IN THE CERRADO BIOME

Globally, Brazil is the world's fifth largest mineral producer. Among the activities that generate environmental degradation in the Cerrado, mineral extraction is one of the most significant for the country's economy, representing about 8% of its Gross Domestic Product (GDP) (IBRAM, 2022). However, mining operations generate severe environmental damage, such as losses of the soil's physical, chemical, and biological characteristics and consequent soil sterility for the occupation of new biological communities (PORTELLA, 2015). Impacts caused by mining also result in various forms of pollution that are targeted by government regulation: water pollution, air pollution, noise pollution, land subsidence, and hydrological contamination (YANG; HO, 2019; AGBOOLA *et al.*, 2020). Revegetating a degraded environment can mitigate erosive processes and allow an ecosystem to recover. Therefore, in addition to reconstituting the chemical, physical and biological components of the soil, it is important to identify specific plant successional groups that are better adapted to the different recovery stages (PEREIRA; RODRIGUES, 2012).

The recovery of areas degraded by mining must be initiated before extractive operations by planning excavation layout and restoration goals (COSTA *et al.*, 2005; CORRÊA, 2007). This is required so that the removal of vegetation cover and the surface layer of the soil can be managed to reduce the costs of recovering ecological damages. A significant part of the resilience of natural ecosystems is located on the surface layer of the soil, which concentrates organic matter, seeds, nutrients and organisms that determine the structural configuration of vegetation (CORRÊA, 2007). Mining prevents the natural regeneration of Cerrado areas due to the removal of the soil surface, which causes even more economic and structural damage to the environmental recovery process (RIBEIRO *et al.*, 2018).

Plant recruitment on mining substrates in Cerrado may occur in part from the regrowth of roots that remain buried in the substrate after mineral extraction. These roots may germinate in the presence of specific physical, chemical, and biological soil conditions, which, in the case of exploited deposits, are below the essential parameters for establishing plant biota. The role of the root system in the Cerrado biome is essential for its conservation. The savanna is often referred to as an 'upside-down forest' because the majority of biomass is found in the root systems rather than the aboveground vegetation (HARIDASAN, 2000; CORRÊA, 2007). Few species have seeds capable of germinating and establishing themselves on mined substrates (CORRÊA, 2007). However, some native herbaceous species, such as those of the genus *Stylosanthes* (Fabaceae family), have been reported to be efficient in establishing themselves and in delaying the recruitment of invasive plants from ecosystems undergoing restoration in the Cerrado (STARR *et al.*, 2013).

The reahabilitation protocols of mining areas have varied (YANG *et al*., 2018; BALDUÍNO *et al*., 2020). The incorporation of sewage sludge into exposed substrates is a technique that provides organic matter and nutrients while reusing the waste produced by sewage treatment plants (CORRÊA *et al*., 2010; SILVA *et al.* 2015; WIJESEKARA *et al*., 2016; LIMA; CORRÊA, 2021). Organic matter and nutrients in sewage sludge improve the physical, chemical and biological characteristics of the exposed substrate, increase its fertility and serve as a means for plant establishment (CORRÊA; BENTO, 2010; LI *et al*., 2013; BONINI *et al*., 2016; BALDUÍNO *et al*., 2020; LIMA; CORRÊA, 2021).

The use of sewage sludge in Brazil is regulated by Resolution No. 498/2020 - CONAMA and Resolution No. 003/2006 by the Federal District Environment Council (CONAM/DF). According to these regulations, there are restrictions on the agricultural use of sewage sludge produced in the Federal District, leading to its predominant application in mined areas (CORRÊA, 2007). Research has demonstrated that quantifying and qualifying ecological attributes and indicators in ecosystems undergoing recovery is crucial for understanding the processes and filters governing community assembly during succession (SUGANUMA; DURIGAN, 2015; CAVA *et al*., 2016; DURIGAN; RATTER, 2016; HALASSY *et al*., 2016; GAVITO *et al*., 2021;WALLACE *et al*., 2022). However, few studies have evaluated plant recruitment and the physical, chemical, and biological characteristics of mining substrates following the application of sewage sludge in the Cerrado (BALDUÍNO *et al*., 2019, 2020). Similarly, studies on the influence of edaphic conditions on plant colonization in mining sites are scarce (STARR *et al*., 2013).

In terms of edaphic conditions, the significant availability of nitrogen in rehabilitated soils in the Mediterranean region could lead to the extensive invasion of ruderal plant species. This invasion may impede ecological succession and pose a risk to the underground aquifer system, especially if heavy metals are present (CARABASSA *et al*., 2018). Therefore, ensuring the correct dosage of sewage sludge is essential to recover essential soil attributes without risking environmental contamination (CARABASSA *et al*., 2018).

The benefits of ecological recovery of degraded areas can be amplified by the mediation of iron in stabilizing soil carbon, since the application of sewage sludge increases soil pH and iron concentration (CORRÊA, *et al*., 2010, 2012), providing optimal conditions for carbon accumulation. Silva *et al.* (2015), using isotopic and elemental analyses, found that the accumulation of carbon derived from plants was triggered by the formation of organic complexes coordinated by iron, which were stabilized in physically protected fractions of the soil. These complexes served as nuclei for aggregate formation and reflected the synergistic effect of biological, chemical, and physical carbon stabilization mechanisms in developing soils (SILVA *et al*., 2015). This shows the importance of considering the interactions between autogenic succession, nutrient dynamics, soil-plant interaction and soil development in determining the success of ecological recovery. Managing these interactions enables the increase of terrestrial carbon sequestration and accelerates the recovery of degraded areas by mining.

Mined tropical soils are difficult to recover and the difficulties increase if efforts focus only on the application of inorganic fertilizers and the subsequent planting of native species. In this way, the chemical processes of soil regeneration remain in a low-energy steady state. Silva *et al.* (2015) concluded that the use of organic matter combined with iron correction is an important intervention for soil development and successful ecological recovery. Coordination of metals is a key step in early soil development, intersecting biological, chemical and physical processes in carbon stabilization (MELTON *et al.* 2014; PARIKH *et al.*, 2014).

Soil carbon stock is considered the largest reservoir in the terrestrial biosphere and a critical part of the global carbon cycle, which can act as a source or sink depending on land management activities (LAL *et al.*, 2021). Soils degraded by mining and other activities are depleted of their carbon stocks, and a possible solution to recover the quality, functionality, vegetation cover, and carbon sequestration capacity of the soil could be the application of organic amendments (SORIA *et al.*, 2021). Considering the amount of sewage sludge generated in wastewater treatment plants, it can become an important raw material for the sustainable production of organic-mineral fertilizers from locally available renewable resources, with a low carbon footprint (CHOJNACKA *et al.*, 2023). In this sense, sewage sludge provides an essential supply of nutrients that stimulate the process of autogenic succession and the continuous deposition of plant materials, promoting soil development and the recovery of its carbon sequestration capacity (SILVA *et al.*, 2015).

Some of the chemical coagulants commonly used in sewage treatment include aluminum sulfate, ferric chloride, and polyelectrolytes. These coagulants have been added during the tertiary treatment of sewage sludge for the removal of phosphorus from the treated effluent discharged into water bodies, which influence the quality of the sewage sludge for specific uses (TIAN; LIU, 2020; BADAWI *et al.*, 2023). Hereupon, tertiary sludge treated with chemical coagulants contains a large amount of iron and/or aluminum hydroxides and is therefore physically and chemically superior to other wastes. Tian *et al.* (2013) found a notable increase in organic carbon stability under long-term sewage sludge application, which depended not only on iron but also on nutrient dynamics. In this sense, there is a critical role in the succession of plants as regulators of the availability of limiting resources and in the management of invasive species in long-term recovery projects, even though the increase in soil carbon sequestration is emphasized (SILVA *et al.*, 2015). It is possible to increase terrestrial carbon sequestration regardless of limiting environmental controls to the extent that ecological and biogeochemical processes are harnessed to accelerate the recovery of degraded lands.

Regarding water availability in mining substrates treated with sewage sludge, studies by Lima and Corrêa (2021) found a 16% increase in water availability compared to the mined substrate that did not receive sewage sludge. This showed similarity with the amount of water made available by the

Cerrado soil in the experiment. According to their study, the increase in water availability was explained by the significant increase in microporosity after the revegetation process. With a significantly greater number of pores, the sludge-treated substrate had more void spaces that could be filled by water after precipitation. This made a significant amount of water available to be used by vegetation (LIMA; CORRÊA, 2021). The study by Oliveira (2015) corroborated the efficiency of sewage sludge in improving the physical properties and fertility of mined substrates, evaluating the texture, particle density, soil density, concentrations of carbon, nitrogen, biomass, carbon, microbial activity, and basal breathing in these materials. The set of ecological succession in mining areas treated with sewage sludge can establish vegetation that reflects the recovery of the soil's productive capacity (LIMA; CORRÊA, 2021). The knowledge about the moisture regime of revegetated substrates treated with sewage sludge can, therefore, provide more appropriate choices throughout the recovery process of a mined area.

Studies by Silva *et al.* (2013) utilized a chrono sequence spanning 14 years to investigate the mechanisms of resource input and spontaneous plant colonization promoting the revegetation and reconstruction of mined soils in central Brazil. Their results showed an unprecedented accumulation of carbon in mined soils treated with sewage sludge, the effect of resource input, and the invasion of exotic grasses. Furthermore, the input of nutrient-rich sewage sludge stimulated the establishment of a diverse, native plant community that was progressively excluded by invasive grasses, limiting nutrient availability but contributing to more than 65% of the total organic carbon accumulated in the soil (SILVA *et al.*, 2013). These results demonstrate that soil-plant feedbacks regulate the amount of available resources and that it is difficult to predict whether soil carbon levels can be maintained without exotic grass cover.

External inputs promote plant colonization, soil formation, and carbon sequestration at the cost of excluding native species (SILVA *et al.*, 2013). For this reason, introducing native woody species could suppress invasive grasses and increase nutrient availability, even though the massive accumulation of carbon in the soil has been wholly dissociated from equivalent changes in vegetation cover. The synergistic effects of resource input and species invasion can be beneficial, with the restoration of soil productivity and vegetation cover, or harmful, by forming resilient systems with low species diversity (SILVA *et al.*, 2013). These conclusions show that ecosystems undergoing recovery can reach different targets, with multiple possible futures defined by converging processes of soil and vegetation. This shows that soil-plant feedbacks determine crucial points for the equilibrium or the imbalance in ecosystems.

Therefore, integrated soil and vegetation analyses are essential to evaluate and mitigate adverse impacts on degraded areas in recovery processes. Likewise, soil development and competition for resources are interdependent processes (CASPER; CASTELI, 2007) that cannot be assessed separately in the restructuring of plant communities in degraded areas. Thus, the use of sewage sludge in mine substrates creates an edaphic environment favorable to plant development but chemically and physically distinct from the original soil of the area (CORRÊA, 2007; SILVEIRA *et al.*, 2018; BALDUÍNO *et al.*, 2019; BALDUÍNO *et al.*, 2020; LIMA; CORRÊA, 2021). These differences between the revegetated substrate and the original soil may reflect the low floristic similarity between plant communities recruited in mined areas and those present in native ecosystems (BALDUÍNO *et al.*, 2020). Chemical analysis and the correct application rate of sewage sludge are essential to avoid either shortage or excess of nutrients in soils where plants will recruit. In this sense, the relationships between plant recruitment and edaphic parameters show that the edaphic environment built with sewage sludge acts as an ecological filter in the assembly of distinct plant communities since it tends to boost the recruitment of invasive species (BALDUÍNO *et al.*, 2019).

Using sewage sludge for revegetation of mined areas is a good alternative that allows recovery and recycling of waste, promotes an increase in the quality and stability of restored areas, reduces the risk of soil erosion, and increases soil fertility. One of the most important parameters to determine the application rate of sewage sludge is the concentration of nitrogen in this residue to avoid the contamination of aquifers by nitrate. In addition, an assessment of sludge suitability, mineral substrates, and location is mandatory before application to avoid contamination and harmful impacts in inhabited areas and close to water bodies (RIBEIRINHO, 2015; CARABASSA *et al.*, 2018; BALDUÍNO *et al.*, 2019; BALDUÍNO *et al.*, 2020). As an important alternative and an opportunity to solve nitrogen availability problems in fertilizers, sewage sludge (including activated sludge) can contain up to 6 - 8% of nitrogen by dry matter (CHOJNACKA *et al.*, 2023). Considering the amount of sewage sludge generated in wastewater treatment plants, it can become a crucial raw material for the sustainable production of organic-mineral fertilizers from locally available renewable resources, with a low carbon footprint.

RECOVERY OF DEGRADED AREAS AND ASSOCIATED ECOLOGICAL PROCESSES

The main challenge of planning the recovery of degraded areas is to reconstruct an edaphic layer similar to a superficial soil horizon which may support ecological succession (FENG *et al.*, 2019). In this way, one or more factors of soil genesis can interfere and help accelerate its formation. Therefore, in recovery efforts, the first two measures are (i) to identify and diagnose the degradation processes active in the area and (ii) to analyze local environmental consequences. For this, it is necessary to use indicators that quantitatively and qualitatively translate the degree of existing degradation and allow the estimation of technical and economic efforts that should be invested in the recovery (HUALIN *et al.*, 2020a; HUALIN *et al.*, 2020b). The definition and need for using indicators for the assessment and monitoring of natural ecosystems have been discussed, but no single indicator can describe and quantify all aspects of soil quality (GARRIGUES *et al.*, 2012; LAL, 2018). Thus, there must be a relationship between all soil properties, which implies the need to select a minimum number of attributes to be evaluated. The criteria for selecting indicators are related mainly to the use of their performance in ecosystem processes (PALMER; RUHI, 2019). They shall integrate physical, chemical and biological properties, and deal with climate variations (LEHMANN *et al*., 2020).

Adding nutrients to mining substrates is essential for ecosystem recovery. Various sources of organic material have been used to improve the properties of degraded soils. Studies have shown that leguminous plants in degraded soils have contributed to reducing soil acidity and increasing the concentrations of exchangeable levels of K and Mg (AGEGNEHU *et al*., 2019). The use of cover crops combined with crop rotation (corn and soybean) under direct seeding improved soil physical properties, such as porosity, soil density, and mechanical resistance to penetration (BARTZEN *et al*., 2019; SATTOLO *et al*., 2021). An alternative that can accelerate the recovery of degraded areas is the use of native species together with species that accelerate the chemical and physical balance of the soil. Green manures are essential for the initial soil coverage and have great relevance for rebalancing ecosystem functioning (CARDOSO *et al*., 2022).

In the Cerrado biome, the development of the herbaceous layer is more important in the recovery of the physical, chemical and biological parameters of mined substrates than mechanical and chemical treatments applied before the sowing herbaceous species, such as *Stylosanthes* spp. (SILVA; CORRÊA, 2010) The development of the herbaceous layer on mined substrate reduces its density and increases water infiltration capacity, available phosphorus contents, total nitrogen, and cation exchange capacity. The organic matter contents in the revegetated substrate approached the levels found in non-mined soils. The microbial carbon biomass, a parameter that reflects the qualitative characteristics of the substrate, remained below the values found in non-degraded soils. The primary production of the lowland stratum of a typical Cerrado was estimated as 3.27 Mg ha^{-1}, with an important contribution from species of the Poaceae family, representing 68 - 78% in the studies by Batmanian and Haridasan (1985). Thus, the recomposition of the herbaceous extract has great importance for the recovery of degraded areas. In addition, the first phase of ecological succession in tropical savannas occurs through the herbaceous stratum, which is the first to colonize degraded areas (SILVA *et al*., 2012).

In addition to the recovery of the herbaceous layer, the soil biota plays an essential role in ecosystem functionality, especially in biogeochemical cycles (WAKSHUM *et al*., 2018; ARCE *et al*., 2019), with direct influence on ecological succession, plant abundance, and diversity (BARDGETT; VAN DER PUTTEN, 2014). Spatial patterns of soil biodiversity are formed by a hierarchy of environmental factors, population processes, and disturbances operating at different temporal and spatial scales (WU *et al*., 2011; BARDGETT; VAN DER PUTTEN, 2014; XUE *et al*., 2022). Soil fauna plays an essential role in the food chain, accelerating population growth and intensifying the activity of microbial populations responsible for the mineralization and humification of organic matter through the supply of nutrients available to plants (KORBOULEWSKY *et al*., 2016). Edaphic fauna also contributes strongly to soil structuring, influencing the mix of organic and mineral particles, the redistribution of organic matter, and the production of fecal pellets. (SOBUCKI *et al*., 2021). Thus, the soil fauna is essential for the recovery of degraded soil attributes.

The revegetation of a mined area includes more than the rehabilitation of physical, chemical, and biological edaphic attributes. It must include the knowledge of the native species and its wide distribution in the target biome to define the best recovery strategies and the use of the different techniques described by Embrapa (Embrapa, [s.d.]; RIBEIRO *et al*., 2018). These strategies range from natural regeneration without management (low intervention) to those carried out exclusively by plantations (high intervention), both targeting natural succession processes (BRANCALION *et al*., 2015; SAMPAIO *et al*., 2015). When planning recovery, it is essential to consider all vegetation strata. This includes, in addition to trees, herbaceous and shrubs. As the Cerrado is formed by a mosaic of savanna, grassland, and forest phytophysiognomies (RIBEIRO *et al*., 2018), restoration projects in this biome must define the plant species to be used. The project should include measures to isolate the area, such as fences, to prevent entry and trampling by animals, control competing plants, exclude leaf-cutting ants, and avoid soil erosion. Construction/maintenance of firebreaks to control and manage fire are also needed. These measures are essential to facilitate plant recruitment after planting or even by natural regeneration (SAMPAIO *et al*., 2015). Thus, planning the environmental recovery of a degraded area is essential for attaining success - this includes the choice of techniques, the species to be used, and knowledge about the biological history of the area on temporal and spatial scales.

The Society for Ecological Restoration (CLEWELL *et al*., 2004) published the guideline "SER International Principles on Ecological Restoration - PRIMER," which provides a list of nine attributes of recovered ecosystems, among other recommendations. A full review of all these attributes is not necessary to consider in a recovered ecosystem. All that is needed is to know that these attributes demonstrate an appropriate trajectory of ecosystem development oriented towards the desired goals or reference. The nine attributes are (1) diversity and similar community structure compared to reference sites; (2) the presence of native species; (3) the presence of functional groups necessary for long-term stability; (4) the ability of the physical environment to support reproductive populations; (5) normal operating mode; (6) the integration with the landscape; (7) the elimination of potential intrusions; (8) resilience to natural disturbances; and (9) self-sustainability. Other attributes may gain relevance and should be added to this list, as they are identified as goals of the recovery project (CLEWELL *et al*., 2004. In any case, recovery processes must direct efforts to follow these attributes.

Among management techniques suitable for increasing the contribution of native species in communities under recovery and dominated by invasive species of the Poaceae family is the use of herbicides (THOMAS, 2017; SILVEIRA *et al*., 2018). It is the most economical alternative compared to other control methods (HEAP; DUKE, 2018; WEIDLICH *et al*., 2020). This technique, associated with the use of fire, reduced the presence of invasive grasses in grassland and savanna ecosystems in tropical regions and opened space for the recruitment of other species (PILON *et al*., 2018; BUISSON *et al*., 2019; DAIREL; FIDELIS, 2020). Likewise, herbicide application to pastures stimulated natural regeneration in Cerrado areas (CAVA, 2014; CAVA *et al*., 2016, 2018).

Plant communities invaded by exotic species, but containing residual native vegetation, can be partially restored through annual weed control (MANTOANI *et al*., 2016; ASSIS *et al*., 2021; BAO *et al*., 2021; LAZARUS; GERMINO, 2022). Weeds are most common in open, sunny locations, where they quickly spread their propagules and prevent the regeneration of native vegetation. (MACHADO *et al*., 2013). A previous fire associated with herbicide application can achieve good results for controlling invasive annual grasses (*Taeniatherum caput-medusae*), increasing plant diversity and facilitating a positive response of functional groups (JAMES *et al*., 2015: GORNISH *et al*., 2016; BALDUÍNO *et al*., 2019; SCHROEDER *et al*., 2022). In parallel, removing invasive plants by hand weeding or herbicide resulted in higher plant biomass, species richness, and regeneration of trees in a North American temperate forest (WEIDLICH *et al*., 2020). In natural ecosystems invaded by exotic species of Poaceae, the application of the herbicide Glyphosate, alone or combined with other techniques, significantly reduced the dominance of these invaders and enabled increases in richness, abundance, and coverage of native species in communities that re-colonized the studied areas. (FLÓRIDO, 2015; MANTOANI *et al*., 2016; THOMAS, 2017).

Controlling the action of biotic filters such as competition, dispersion, and predation, and abiotic filters like compacting of the soil surface can indistinctly result in general increases in plant species richness and diversity. Likewise, chemical control of weeds followed by direct seeding of native species can substantially reduce the spread of weeds (*Urochloa brizantha*). However, this management was not able to prevent colonization by other exotic and invasive ruderal species from the Cerrado (BALDUÍNO *et al*., 2019; BALDUÍNO *et al*., 2020).

The natural course of ecological succession in a mined area begins with the arrival of propagules and the establishment of an initial community dependent on the species that overcome several abiotic and biotic filters (HULVEY; AIGNER, 2014; BALDUÍNO *et al*., 2019). Among the abiotic filters are the availability of water and nutrients, pH and soil compaction and fertility, for example (CLELAND *et al*., 2013; SOLLENBERGER *et al*., 2016). Biotic filters may involve ecological relationships of competition, dispersion, predation and parasitism (CLELAND *et al*., 2013; HIGGS *et al*., 2014; RENAULT *et al*., 2018; WONG *et al*., 2019). The intensity of each filter will influence the level of environmental stress involved in the restoration of communities during ecological succession (RENAULT *et al*., 2018). Some studies have suggested that the edaphic limitations of exposed substrates and the pressure exerted by invasive species, especially from the Poaceae family, are the primary ecological filters that restrict the establishment and growth of native species in areas degraded by mining activities in the Cerrado (CORRÊA, 2007; HALASSY *et al*., 2016; SOLLENBERGER *et al*., 2016).

CONCLUSIONS

Among the most effective recommendations reported in the literature to optimize ecological restoration on mined areas are the following considerations: (i) The use of the lowest possible application rate of sewage sludge (< 100 t ha-1 dry basis); (ii) Adoption of integrated management for continuous control of invasive plants in the restoration area, particularly African Poaceae species, which dominate the vegetation cover in these areas; (iii) Planting woody species seedlings and directly seeding herbaceous, arboreal, and shrub species; (iv) Sowing plant species with competitive potential and functional characteristics similar to invasive species, capable of achieving higher cover percentages in the shortest time possible; (v) Increasing the functional diversity of species in established plant communities, with an emphasis on initial colonization by the herbaceous stratum; (vi) Investigating, identifying, and manipulating ecological filters to stimulate the recruitment of native plant species, as soil-plant feedback regulates resource availability in mined substrates treated with sewage sludge; (vii) Considering soil-plant feedbacks determines crucial points for ecosystem balance or imbalance; (viii) Nitrogen recovery from wastewater treatment plants has high potential in the fertilizer sector.

In addition to being an economically viable option for rehabilitating areas degraded by mining, the use of sewage sludge reduces waste sent to landfills and soil erosion, optimizes fertilization and soil structure, provided it is properly treated and applied according to environmental regulations.

The traditional narrative literature review provides a broad and quickly updated description of studies on a topic but does not exhaust all sources of information. Other literature review methods may bring to light new processes not mentioned in this article.

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