

## Review

# Grasses of Campos Rupestres: Diversity, Functions and Perspectives for Seedling Production and Ecological Restoration

Alessandra Rodrigues Kozovits <sup>1,\*</sup>, Maurílio Assis Figueiredo <sup>2</sup> and Maria Cristina Teixeira Braga Messias <sup>1</sup>

<sup>1</sup> Department of Biodiversity, Evolution and Environment, Federal University of Ouro Preto, Campus Morro do Cruzeiro, Bauxita, Ouro Preto 35402-206, MG, Brazil; cristina@ufop.edu.br

<sup>2</sup> Postgraduate Program in Crustal Evolution and Natural Resources, Federal University of Ouro Preto, Campus Morro do Cruzeiro, Bauxita, Ouro Preto 35402-206, MG, Brazil; maurilioafigueiredo@ufop.edu.br

\* Correspondence: kozovits@ufop.edu.br; Tel.: +55-(31)-99168-1595

## Abstract

The Campos Rupestres, ancient and nutrient-poor mountaintop ecosystems in Brazil, harbor exceptional biodiversity and endemism but face severe threats from mining and urban expansion. Native grasses (Poaceae), represented by nearly 300 documented species—many of them poorly studied—are fundamental elements of these ecosystems. They provide critical ecological services, including soil stabilization, enhancing carbon storage and nutrient cycling, regulating water availability, and resilience to disturbances. This review synthesizes current knowledge on the diversity, functions, and propagation of Campos Rupestres grasses, with emphasis on their potential in ecological restoration. Despite their ecological importance, large-scale use of native grasses remains incipient, constrained by limited knowledge of reproductive biology, low seed viability, and scarce commercial seed availability. Advances in propagation include seedling and plug production, vegetative propagation, and rescue/reintroduction strategies, which have shown promising results in post-mining restoration. However, reliance on seed collection from natural populations risks depleting already limited genetic resources, highlighting the need for ex situ production systems. Expanding research on taxonomy, ecology, and cost-effective propagation methods, alongside supportive policy and market development, is crucial for integrating native grasses as cornerstone species in restoration programs. Bridging these gaps will enhance biodiversity conservation and restoration in one of the world's most threatened megadiverse systems.

**Keywords:** tropical and subtropical highland grasses; propagation techniques; recovery of areas degraded by mining; grass germination



Academic Editor: Fabio Gresta

Received: 1 October 2025

Revised: 22 December 2025

Accepted: 5 January 2026

Published: 13 January 2026

**Copyright:** © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

## 1. Introduction

The Campos Rupestres, also named as rocky fields, rocky grasslands, rock outcrop vegetation, and rupestrian grassland, represent a highly diverse mountain ecosystem that intersperse or edge other important biomes in Brazil, such as Atlantic Forest, Cerrado, Caatinga and Amazon Forest. Occupying less than 1% of Brazilian territory, it is estimated to hold around 15% of the national flora [1,2], a fact that cannot be minimized, considering that Brazil is home to the greatest diversity of plants worldwide. More than 100 new species of plants, and growing numbers also of animals, fungi, and bacteria have been described in the last two decades, many of which are already classified as rare or endangered [3–8]. The severe environmental filters, mostly related to the extremely oligotrophic, shallow and

often discontinuous soils, enhance the effects of climatic seasonality on the availability of water and nutrients, which may underline the extraordinarily high endemism [9] and wide array of, in some cases, unusual specializations and ecological interactions [4,10].

Generally occurring on mountaintops above 800 m, these ecosystems occupy aquifer recharge zones that supply hundreds of small cities and several metropolises, ensuring the subsistence and life quality of millions of people [11]. Many of these ecosystems occur over deposits of Fe, Mn, Al, and other minerals of economic importance to the country. Ornamental stones and quartzose sand (for civil construction and glass manufacturing) are also resources exploitable in these areas. More recently, due to their privileged position in the landscape, Campos Rupestres have also suffered from real estate expansion and uncontrolled tourism [11]. All these factors, combined with ongoing climate change, place Campos Rupestres among the most threatened ecosystems in the world [4]. Under different climate and land-use scenarios, these authors modeled a reduction of ca. 82% in the Campos Rupestres area in Brazil by 2070. The effect of mining is most seen in the Iron Quadrangle region, where a 213% increase in mined area was observed between 1985 and 2011, representing a reduction in native vegetation of over 3000 hectares [12]. Species such as *Comanthera elegans* and the entire genus *Vellozia*, which includes many microendemic species, appear to be especially sensitive to climate change, with alarming estimates of suitable habitats losses up to 50% and 85% by 2050 and 2060, respectively [13,14]. In response to climate change alone, the distribution area of the threatened *Arthrocerus glaziovii* may expand. However, projected areas of occurrence overlap with various mining concessions, implying a high probability of future exploitation [15]. Losses of area and biodiversity obviously mean disruptions in the provision of ecosystem services, with serious consequences for human well-being, including the subsistence of traditional communities. Unfortunately, less than 10% of its total area is within any type of effectively implemented conservation unit (see [11] for detailed information on ecosystem services provided by Campos Rupestres, major threats and proposed actions for its sustainable use).

These tragic predictions exacerbate the urgent need for the increase in protected areas and developing technologies for restoring the impacted ones [4,11,13,14,16]. Thus, knowledge about the propagation of native species, such as grasses and other plant families of high value and importance in the ecosystem, is extremely necessary to support the restoration of these areas.

So far, there are no commercial nurseries for this flora. In addition, there are few published records of Campos Rupestres native species propagation, most of them for seedling production of woody species. Given that herbaceous plants, especially grasses, account for the vast majority of species in Campos Rupestres—often exceeding 85% of the flora (see Section 3)—ecological restoration efforts should prioritize the reintroduction and establishment of this stratum. The optimization of grass seed germination and seedling production relies not only on basic knowledge about species biology, but also on advances in the development of commercial-scale cultivation systems, seed collection and production chains, and the continuous updating of environmental legislation.

This review aims to synthesize current knowledge on the diversity, ecological functions, and propagation of native grasses in Campos Rupestres, with emphasis on their use in ecological restoration. In contrast to previous reviews that primarily address floristic patterns, ecosystem processes, or woody species, this study focuses on grasses as key functional components, integrating evidence on reproductive biology, propagation techniques, and restoration outcomes. This approach allows the identification of practical limitations, knowledge gaps, and research priorities relevant to the large-scale use of native grasses in restoration programs.

## 2. Methods

### 2.1. Literature Review

Ecological information for Poaceae species occurring in Campos Rupestres was compiled through an extensive review of scientific articles, monographs, and theses published up to 2025. The bibliographic survey was conducted using the ‘Web of Science’, ‘SciELO’, and ‘Scopus’ databases, employing the following keyword combination in both Portuguese and English: TS = (Poaceae OR Gramineae OR Grasses OR Gramíneas) AND TS = (“campo rupestre” OR “rupestrian grassland” OR grassland\* OR “complexo rupestre” OR “rupestrian field” OR “rock outcrop” OR “ferruginous campo rupestre” OR “campo rupestre ferruginoso” OR “campo ferruginoso” OR “quartzitic campo rupestre” OR “campo rupestre quartzítico” OR “iron canga” OR canga\* OR Cerrado) AND TS = (germinação OR germination OR germinabilidade OR germinability OR ecology OR ecologia OR restoration OR restauração).

From the total pool of retrieved publications, we selected only those reporting germination experiments on species listed as occurring in Campos Rupestres (see Supplementary Materials Table S1). Studies were included even if the seeds used in the experiments were not collected specifically from Campos Rupestres areas.

### 2.2. Database of Poaceae Species in Campos Rupestres

Plant records were retrieved from the Flora and Funga of Brazil [17] and the species-Link network [18] databases. We included records collected up to the year 2025. Additionally, we supplemented the database with species and data from taxonomic revisions and floristic surveys of Campos Rupestres focusing on Poaceae, e.g., [19–21]. Intraspecific taxa were not included in the dataset. Scientific names were verified and updated according to the Flora and Funga of Brazil [17].

## 3. Geological and Evolutionary Context

Campos Rupestres can be defined as OCBILs, Old, Climatically Buffered, Infertile Landscapes (sensu Hopper [22]), since they are ancient ecosystems, whose communities co-evolved with shallow, infertile soils (extremely phosphorus-limited; [23,24]) that developed for thousands of years over stable tectonic areas and under very specific climatic conditions [2,25,26]. In South America, these OCBILs can be found with concentrations in Brazil, particularly in regions such as the Iron Quadrangle [27–31], Espinhaço Range [32–34], Chapada Diamantina [35,36] and Serra dos Carajás [37–39]. These areas are portions of the Earth’s crust, contained within a single geotectonic unit known as the South American Platform [40,41], formed and stabilized in the Archean and affected on its edges during the Proterozoic, but without important tectonic events during the Quaternary [41–43].

The structure of the geological compartments that characterize modern-day Campos Rupestres was determined by Proterozoic tectonic activity that folded and faulted the rocks during mountain-building processes, leading to a high regional landscape heterogeneity, modified by weathering and erosion processes related to the climatic oscillations during the Quaternary [34,42]. Due to this Quaternary geological and climatic evolution, most of Campos Rupestres developed on a mosaic of rocky outcrops and sandy/stony shallow soils derived from quartzites, banded iron formations and sandstones [1,2,25,42]. These rocks are among the most resistant in terms of chemical and physical weathering, which was decisive in determining the high altitudes (>800 m) where most Campos Rupestres are found [12,44,45], creating a kind of mountaintop “isolated island” [28,42]. Although these highland regions are currently subjected to distinct climatic regimes, the Campos Rupestres—as with all OCBILs—developed under strong climatic buffering, characterized by pronounced dry seasons, high solar radiation, and marked daily temperature fluctua-

tions (except for areas located in the Serra dos Carajás). These environmental constraints have driven the evolution of highly specialized plant species [1,2,10,45,46], particularly within the Poaceae [47].

## 4. Why Should We Consider Grasses for the Recovery of Degraded Areas of Campos Rupestres?

### 4.1. Diversity and Abundance of Native Grasses in Campos Rupestres

Brazil harbors the richest flora in the world, with more than 46,000 species [17]. Although Campos Rupestres occupy less than 1% of the Brazilian territory, they host more than five thousand vascular plant species, over 40% of which are endemic to this ecosystem [2]. Poaceae is among the four most species-rich families of the Brazilian flora and stands out in Campos Rupestres for both richness and abundance [19]. A checklist compiled from herbarium databases and scientific publications (Table S1) indicates that native grasses in the Campos Rupestres comprise 296 species distributed across 79 genera [17,18]. However, this number is likely underestimated. For instance, approximately 10% of the records in the SpeciesLink database [18] are identified only at the family level, and almost 25% only at the genus level. This highlights that further floristic and taxonomic studies remain necessary to fully understand the ecological roles and adaptive strategies of these grasses.

The campos rupestres are mostly associated with the Espinhaço Range where there were 340 grass species registered in all kinds of open ecosystems [19]. These inventories also reveal the remarkable degree of endemism characteristic of Campos Rupestres [2]. More than 100 species (113) of Poaceae are endemic to Brazil, and several of them are restricted to Campos Rupestres, suggesting unique adaptive strategies to the restrictive edaphic and climatic conditions of this ecosystem [48].

In floristic surveys carried out in Campos Rupestres in Minas Gerais, Mato Grosso do Sul and Pará states, Poaceae emerged as the family with the greatest species richness [27,39,49–56] or ranked among the four families with the highest number of species [28,57–65]. In some phytosociological studies conducted in Campos Rupestres of the Iron Quadrangle in Minas Gerais, Poaceae was identified as the family with the highest importance value index, or some of its species presented the highest importance value compared to other species in the community [18,51,54,63,65].

The most species-rich genera of Poaceae recorded in floristic surveys are *Paspalum* (59 spp.), *Axonopus* (25 spp.), *Dichanthelium* (15 spp.), *Andropogon* (14 spp.), *Mesosetum* (12 spp.), *Eragrostis* (11 spp.), and *Apochloa* (10 spp.), all of which contribute substantially to the ecological complexity of this biome. Several species are endemic to Campos Rupestres, especially those from *Paspalum* [17]. Research in this sense is still ongoing, and many species known only from their type-material may be narrow endemics or microendemics to specific mountain ranges or even single locations, such as *Paspalum giuliettiae* [17]. In addition to its ability to colonize post-mined areas and initiate the aggregation of unstructured topsoil particles [66,67], it is expected that the native grasses play all other key ecological roles typically described for the family in open ecosystems around the world, including soil stabilization, water retention, and the provision of habitat and resources for numerous organisms [68–70]. Furthermore, some species have been highlighted as keystone taxa, fundamental for maintaining biodiversity in grassland ecosystems such as *Aristida flaccida* and *Trachypogon montufari* [48]. Studies on ecological succession in degraded Campos Rupestres have revealed Poaceae as one of the most species-rich taxa during the initial stages of community reestablishment [71–73].

More than ten Poaceae species are classified as endangered on the IUCN Red List [74], underscoring both the importance of conservation and the vulnerability of native grasses

in these ecosystems [20]. The presence of such species reflects not only high biological value but also the ecological and evolutionary processes that generate and maintain diverse microhabitats and ecological niches in Campos Rupestres.

The documented pressures affecting Campos Rupestres, including mining and urban expansion, land-use change, and climate-driven habitat contraction, directly threaten grass diversity and abundance, with cascading consequences for ecosystem functioning and resilience [4,11,13–15]. In addition, invasive alien species used in revegetation practices, particularly those of the genera *Urochloa* and *Melinis* [48,75], constitute an additional and significant threat. As dominant components of the herbaceous layer, native grasses regulate soil stability, surface hydrology, nutrient cycling, and early successional dynamics [66–70]; their loss or replacement by invasive species compromises these processes and reduces the capacity of degraded sites to recover. Given their functional traits, high local adaptation, and central role in ecosystem processes, the re-establishment of native grass assemblages is therefore a critical prerequisite for effective restoration, particularly in highly degraded environments where natural regeneration is limited.

Based on the observed results, there is a clear need to advance research in ecology, physiology, and taxonomy of native grasses. Such knowledge is essential to support ecological restoration strategies in Campos Rupestres, ensuring the effective use of native grasses as key components for restoring biodiversity, ecological processes, and the resilience of these unique ecosystems.

#### 4.2. Ecological Functions of Native Grasses

The Poaceae family plays critical ecological roles in ecosystem functioning, presenting a set of structural and physiological traits that allowed them to be dominant in many of the most extensive open ecosystems worldwide and to perform efficiently in degraded areas [66–70]. The aboveground architecture, which is quite variable, organizes the narrow leaves and hollow stems in such a way as to optimize light interception in open environments [76]. The C3 and C4 species exhibit highly adjustable photosynthetic capacity and water use efficiency in a wide range of climates [26,70,77,78]. Furthermore, grasses are endowed with the ability of growth from basal meristems and often have persistent buds at belowground level, characteristics of major importance related to resilience to fire, frost, drought, and grazing, since these allow rapid resprouting after disturbances [10,79–81]. There is evidence that fire induces the flowering initiation and seed germination of some Cerrado grasses [82,83] and that terminal buds are protected in the center of tussock grasses [10]. Although seed dispersal and sometimes photosynthesis is facilitated by specialized structures in the spikelets [70,84], grasses very often invest in vegetative reproduction, what is a clear ecological advantage. Compensatory clonal growth via tillers, rhizomes, or stolons is the primary mode of propagation and regeneration after disturbances in many grasslands, sustaining productivity and rapidly expanding populations, especially where seedling establishments are rare or unreliable [80,81,85–88].

The root architecture of tropical grasses may vary significantly and is finely tuned to the environmental gradients [89]. Grass roots might be more efficient than trees in water absorption, presenting larger xylem vessels and higher axial hydraulic conductivity [90]. In addition to fixing the plant to the substrate, the root systems play a fundamental role in stabilizing soil and influencing carbon, nitrogen, and phosphorus stocks and cycles [91–93]. In fact, grasses contribute to about 33% of terrestrial primary productivity, supporting food webs [94]. In the Brazilian savanna formations where trees are not present and grasses dominate, the estimated above and belowground carbon stocks are, respectively, 1.8 and 7.6 Mg C ha<sup>−1</sup> [93]. In tropical savannas, grass-derived carbon constitutes more than half of total soil organic carbon (SOC) to a soil depth of 1 m [95]. Information on the SOC stocks

stored in undisturbed soils under native vegetation is fundamental to decision makers, since they provide a baseline for evaluating land-use change impacts and the further C sequestration gained with restoration efforts [96]. In this recent data-paper, these authors highlight the relevance of grassy ecosystems in Brazil as a C sink. The 0 to 100 cm depth SOC stocks across major grassy ecosystems in Brazil varied from 7.6 Mg C ha<sup>-1</sup> in the Campos Rupestres to 366 Mg C ha<sup>-1</sup> in the South Brazilian highland grasslands.

Studies carried out with focus on the ecophysiological attributes of native grasses in Campos Rupestres are still rare, but the data obtained so far reinforces the high adaptive capacity of this group to respond to environmental gradients and disturbances. In general, grasses in the Campos Rupestres predominantly occupy the areas or microhabitats with the shallowest soils [97] and might present more than five times higher investment in aboveground than in belowground biomass [98]. Under such highly restrictive conditions in terms of water and nutrient availability, and for root development, it is not surprising that in comparison to other Brazilian grasslands, a higher proportion (60 to 85%) of C4 grass species were registered in the Campos Rupestres in the Espinhaço Range [21]. Some grasses, as well as plants of other families in the Campos Rupestres, proved to be sensitive to the seasonal water availability, reducing stomatal conductance and the pre-dawn and midday water potential values during the dry season [99].

In fact, as demonstrated by Negreiros et al. [100], abundant grasses in the southern portion of the Espinhaço mountain range, such as *Mesosetum exaratum*, *Tatianyx arnaces*, *Paspalum erianthum* and *Homolepis longispicula*, are classified as highly stress tolerant. The latter also has striking features of the competing strategy according to Grime & Pierce [101]. Using a similar approach, Fernandes et al. [102] found that native grasses seemed to be more efficient in terms of stress tolerance than the invasive species. The advantage of native species over introduced ones in leading to drought was confirmed consistently in grasslands worldwide [103]. In Campos Rupestres, orographic fog occurs throughout the year and constitutes a major source of water and nutrients during the dry season [104]. Fog water can be intercepted and absorbed by the leaf blade (leaf water uptake—LWU) at different velocities and capacities depending on functional groups [105] affecting positively the gas exchange, the tolerance to the excessive light intensity and higher temperatures, minimizing the water stress [105,106]. Trichomes are known to facilitate leaf water absorption [107] and occur in many native grasses [108]. Investigating their role in LWU could broaden the understanding of the functional traits that favor the occurrence and diversity of Poaceae in environments like Campos Rupestres. Superficial root systems, as commonly found in native grasses [108], are normally associated with the rapid use of rain pulses [109] and may also benefit from the presence of fog deposition.

Although light is not a limiting resource in Campos Rupestres, light availability for herbaceous species may vary in response to vegetation structures, the topographic and microtopographic heterogeneity and the self-shading caused by the cespitose growth habit of grasses, such as *Axonopus siccus* and *Eragrostis polytricha* [110]. Comparing a set of morphological and physiological responses of these two C4 species to light variation, these authors found *Eragrostis polytricha* to be a more shade-tolerant species, adjusting its metabolism to optimize energy use and C storage under low light. *Axonopus siccus* apparently would be better prepared to occupy microsites with high incidence of sunlight, exhibiting high maximum CO<sub>2</sub> assimilation, but low morphological plasticity under the lower light environment. These differential responses should be considered when planning the use of grass species for restoration in Campos Rupestres degraded areas subject to different vegetation structures and light gradients.

The vascular flora of the Campos Rupestres exhibits highly specialized adaptations to the nutrient scarcity, especially regarding phosphorus and nitrogen (for a comprehensive

description of ecophysiological adaptations, see [2,10,111,112]). Consistently, the endemic and threatened native grass *Aulonemia effusa* displays strategies such as non-mycorrhizal rhizosheaths, high foliar N:P ratios, and high P-remobilization efficiency during leaf senescence, exceeding 70% [111]. Strategies for increasing the availability of nutrients in Campos Rupestres may involve root associations with bacteria populations enriched in genes related to P and N turnover, and that promote the absorption of organic compounds, as found in two *Vellozia* species [112]. The grass *Paspalum atratum* exhibited significant interactions with local soil biota, influencing nutrient availability and improving soil health through their root systems [113]. Positive effects of bacterial communities captured in reference environments were also observed on the seed germination of two grasses of the genus *Sporobolus* [114]. A mixture of post-mined substrate and commercial soil (1:1) was inoculated with a 1% solution of the bacteria extract (effective microorganisms [115]) seven days before sowing, enhancing germination compared to the control. Inoculating the substrate resulting from bauxite mining with small volumes of topsoil from nearby Campos Rupestres has demonstrated the potential to improve both ex situ seedling production and the establishment and growth of native plants in degraded areas [71,116,117]. The metabarcoding of fungal communities in that degraded area revealed a predominance of pathogens taxa, contrasting with the high abundance and diversity of plant symbionts and decomposers in the reference area [118].

In post-mined areas, plots that received topsoil transposition from Campo Rupestre presented rapid soil particle aggregation around the roots of native grasses recruited from the seed bank [67]. The role of *Echinolaena inflexa* roots in soil structuring and consequent resistance to laminar erosion was also demonstrated, but in an experiment in gullies [119].

## 5. Production of Seedlings, Plugs and Mats of Native Grasses

Grasses stand out both for their species diversity and the abundance of individuals in preserved Campos Rupestres (see Section 4.1; [39,51,64]). However, the incorporation of native grasses into restoration initiatives within this ecosystem remains incipient. This limited application stems from multiple factors, including insufficient awareness regarding the importance of re-establishing functionally equivalent plant communities, limited knowledge of the species' biology, and the scarcity of commercially available propagules for restoration projects [120–124].

Although this ecosystem harbors approximately 300 known grass species, in addition to many others not yet identified (see Section 4.1), only about 75 species have been evaluated with respect to sexual or asexual reproduction (Figure 1, Supplementary Materials Table S2). Figure 1 summarizes evaluations performed solely under standard conditions, that is, providing water for the seeds to soak up, without any other attempt to break (light and temperature variations, application of hormones, acids, or nutrients) or stimulate dormancy (such as darkness). Thus, the range of germination within each species represents possible effects of ecotype (Cerrado or Campo Rupestre), but also small variation in experimental conditions reported or not reported by the authors, such as the storage time of the seeds and others. More than half of these species showed germination rates above 40%. *Aristida setifolia*, *Aristida riparia*, *Ctenium cirrhosum*, *Elionurus muticus*, *Gymnopogon doellii*, *Paspalum reduncum*, *Paspalum trachycoleon*, *Schizachyrium microstachyum* and *Schizachyrium sanguineum* stood out for achieving maximum germination rates very close to 100% [125–131]. *Sporobolus metallicolus*, *Schizachyrium tenerum*, *Saccharum villosus*, *Paspalum pectinatum*, *Paspalum hyalinum*, *Gymnopogon foliosus*, *Eragrostis rufescens*, *Echinolaena inflexa*, *Ctenium chapadense*, *Anthaenantia lanata*, *Andropogon lateralis*, *Aristida torta* and *Aristida recurvata* achieved maximum germination percentages ranging from 80 to 94% [83,117,126,128,130,132–134], indicating a high potential for reproductive success

under the experimental conditions. At the other extreme, 13 species showed germination rates below 10% (*Apochloa euprepes*, *Axonopus barbigerus*, *Axonopus capillaris*, *Axonopus carajasensis*, *Axonopus laxiflorus*, *Dichanthelium sciurotoides*, *Gymnopogon spicatus*, *Panicum campestre*, *Paspalum cangarum*, *Paspalum cinerascens*, *Paspalum glaucescens*, *Paspalum trichostomum*, *Sporobolus ciliatus*) [117,128,134–138], suggesting that their seeds may have an inherent dormancy requiring specific conditions to germinate.

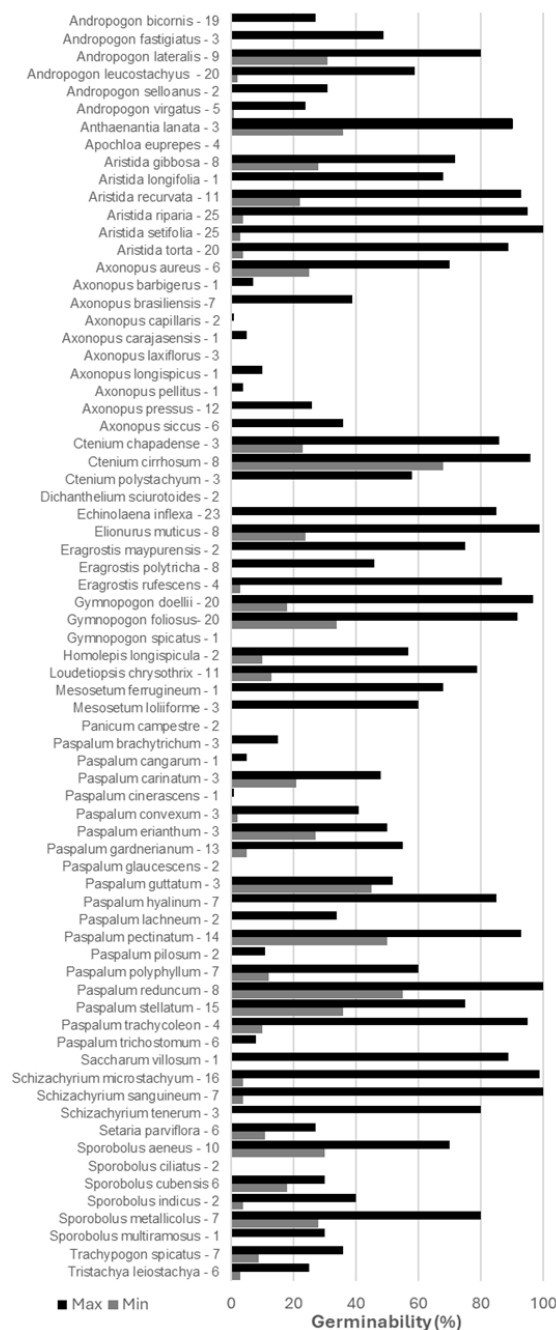


**Figure 1.** Minimum (grey) and maximum (black) germination percentages obtained in various experiments with native grass species from Campos Rupestres in Brazil. The numbers following the species names represent the assessments conducted for each species and considered in this study. Evaluations that included germination in darkness, seed scarification with  $H_2SO_4$ , germination stimulation with  $KNO_3$ , or seed preheating were not considered to determine the minimum and maximum germination, since depending on the species, these treatments can reduce germinability. For further details, and citation of the studies from which the data were taken, see Supplementary Materials Table S2.

The difference between the minimum and maximum germinability indicates the plasticity or sensitivity of the seed to the experimental conditions. Species with a high germination range include *Aristida recurvata*, *Aristida riparia*, *Aristida setifolia*, *Aristida torta*, *Elionurus muticus*, *Eragrostis rufescens*, *Gymnopogon doellii*, *Paspalum hyalinum*, *Paspalum trachycoleon*, *Schizachyrium microstachyum* [81,125,127–131,133–135,139,140], all with variations greater than 70 percentage points. In contrast, the germinability of *Axonopus siccus* and *A. purpusii* seems to be intrinsically low, suggesting deep dormancy or low seed viability that is not easily overcome by the standard experimental conditions.

The heterogeneity of dormancy-breaking methods (Supplementary Materials Table S2) and the lack of important information hinder the synthesis of the effects of different techniques on seed germination. For example, many experiments lack information on the duration and method of seed storage, whether any selection method was used, and how it was carried out. Bearing in mind these factors that make a direct comparison between studies difficult, an initial analysis of the collected dataset (see Supplementary Materials Table S2) demonstrated that there is no “universal protocol”. The ideal strategy to stimulate germination is species-specific, and should be adjusted to the prevalent dormancy mechanisms, and, critically, its ecological provenance (ecotype). Observed patterns indicate the prevalence of physiological dormancy, frequently linked to strict light requirements, thermal fluctuations, or chemical and thermal stimuli that simulate environmental events such as fire.

In general, the seeds of species collected in Cerrado (including Campo Limpo) exhibit, on average, higher germination rates and respond vigorously to basic stimuli such as light and temperature changes. In Campos Rupestres, more severe restrictions (shallow and oligotrophic soils) may result in seeds with deeper or “recalcitrant” dormancy. Many species showed germination close to 0% (e.g., *Axonopus laxiflorus*, *Echinolaena inflexa*) under standard treatments and the average basal germination can be lower than 7%.

A comparison of germination rates under light (12L/12D) and dark (24D) regimes for grass seeds harvested in Campo Limpo, which also occur in Campos Rupestres, reveals an extreme light dependence for several species. For example, *Aristida torta*, *Paspalum pectinatum* and *Schizachyrium microstachyum* exhibited germination rates, respectively, of 68%, 92% and 97% under light at 25 °C, but only 17%, 1% and 12% when kept in the dark. This extreme latency in the dark demonstrates that these species employ a transient or shallow seed bank strategy. The presence of light signals the absence of dense cover (canopy or thick litter) over the seed.

Daily temperature fluctuation (thermoperiodicity) is also an extremely relevant physical signal indicating the proximity of the seed to the soil surface and the absence of an insulating layer of leaf litter. The analysis has shown that temperature variation is a strong germination stimulant for many species, which exhibited significantly higher rates under alternating temperatures (20/35 °C or 20/30 °C) compared to a constant temperature of 25 °C. The case of *Aristida torta* is particularly illustrative: germination under light increased from 40% (25 °C) to 88% under the 20/35 °C regime. Even in the dark, the thermal pulse contributed, raising germination from 13% to 24% under the same alternating conditions. Thermal stimulation proves to be a powerful signal for breaking dormancy, acting synergistically or, in some cases, dominantly in relation to light. The species *Ctenium cirrhosum* achieved 96% germination under alternating temperatures with light, and a remarkable 85% in the dark under the same alternation. For this species, thermal fluctuation appeared to be the dominant dormancy stimulus, almost eliminating the light requirement. This may suggest that lightly buried seeds germinate if the thermal variation on the soil surface is intense. Unlike circadian temperature variations, treatments that expose seeds to abrupt temperature increases of up to 80 °C for a few minutes (2 min) serve to simulate the

passage of fire. Seeds of *Andropogon leucostachyus*, collected in Campo Rupestre, showed a significant increase in germination when subjected to thermal treatment, jumping from 34% (control, light) to 51% (heat at 80 °C). This positive response suggests that heating is an adaptive trigger for breaking dormancy, allowing the species to take advantage of the post-fire environment for establishment. In contrast, other species such as *Andropogon bicornis* and *Setaria parviflora* (both also from Campos Rupestres) did not show any benefit or had a marginal reduction in germinability (from 18% to 14% and from 11% to 14%, respectively). This variation demonstrates that physiological specialization to fire is not universal; heat-insensitive species must have alternative dormancy-breaking mechanisms, such as smoke water (not fully explored in the data provided), nitrates, or strict post-harvest maturation requirements, ensuring an ideal germination time that avoids the dry period immediately after fire.

Potassium nitrate ( $\text{KNO}_3$ ) is widely used in dormancy studies to break physiological dormancy and simulate the increase in available nitrogen in the soil after fire or rapid mineralization of organic matter. The nitrate treatment was effective for *Setaria parviflora* (Campos Rupestres), whose germination increased from 11% (Light) to 25% ( $\text{KNO}_3$ ). However, the most significant interaction occurred with *Eragrostis polytricha*. This species achieved extremely high germination rates (98.5%) when 0.2%  $\text{KNO}_3$  was applied to naked seeds, in contrast to 46.5% under light. This result suggests that the physiological dormancy of *E. polytricha* is critically masked by the presence of physical or chemical barriers (inhibitors) in the seed coats (glumes/spikelets). For seedling production, management requires a combination of treatments that may involve intensive processing to remove the seed coats, followed by priming with nitrate, maximizing the effectiveness of the protocol, and substantially reducing the waiting time.

A significant challenge for restoration is the presence of species with deep dormancy or morphophysiological dormancy, which do not respond to standard laboratory treatments. Species such as *Axonopus laxiflorus*, *Echinolaena inflexa*, and *Apochloa euprepes*, originating from the Campos Rupestres, showed germination of 0% or 1% under almost all initial treatments, including Light,  $\text{KNO}_3$ , and heat at 80 °C. To verify whether dormancy was due to the impermeability of the seed coat, treatment with Sulfuric Acid ( $\text{H}_2\text{SO}_4$ ) was applied. This treatment, which simulates mechanical scarification, failed to break dormancy in *Echinolaena inflexa* and *Apochloa euprepes*. The ineffectiveness of acid scarification indicates that the main restriction does not lie in the physical impermeability of the seed coat, but rather in internal (physiological) factors. The management of these species requires the investigation of more complex physiological requirements, rarely met in germination chambers, such as long periods of cold and wet stratification (simulating cold winters or deep soil conditions) or the application of plant growth regulators (e.g., gibberellic acid—GA3).

Post-harvest seed storage is a fundamental and economically viable method for overcoming physiological dormancy in many grasses, with the temperature during storage a determining factor for embryo maturation. The seeds of *Andropogon leucostachyus* (collected in Campos Rupestres) presented the initial germination of 34% (under light conditions) and increased significantly to 58% after 8 months of storage at room temperature. Conversely, when the same batch of *A. leucostachyus* seeds was stored under refrigeration (8 °C) for the same period, germination dropped to 11%. Refrigeration, while ideal for preserving long-term viability, can inhibit or delay after-ripening. For nursery logistics, this indicates that freshly collected seeds exhibiting physiological dormancy should undergo a controlled period of storage at room temperature to break dormancy before being moved to refrigeration conditions for extended conservation. Seed longevity dictates its usefulness in restoration operations and the ability to maintain multi-year stocks. *Schizachyrium microstachyum*

(Cerrado) demonstrated a pattern of high initial viability (98.8%) and remarkable longevity, maintaining 77.2% germination after 2 years of storage. This resilience makes it a reliable species for the management of persistent seed banks and for the seed trade. However, a most restrictive pattern was observed in *Paspalum reduncum* also in the Cerrado. This species exhibited a “peak and fall” dynamic, with 55% initial germination, reaching a maximum of 100% after 1 year of storage (peak after-ripening), but falling to 0% after 2 years. The behavior of *P. reduncum* seeds establishes a restricted window of use. Logistics management must ensure that seeds with are used in the year following collection, as the loss of viability is rapid and total, making multi-year stock accumulation unfeasible.

While these works provide important baseline information to assess the potential use of these species, they address only an initial stage of the process, since results obtained in laboratories or greenhouses frequently do not reflect the establishment potential in the field, particularly in degraded areas [116,141–143]. Moreover, in addition to the scarcity of ecological and reproductive information on these grasses, the still limited availability of seeds and seedlings on the market further constrains their use in restoration projects. In critical regions, such as the Iron Quadrangle in Minas Gerais, which is characterized by extensive Campos Rupestres areas and intense anthropogenic pressure, there are no systematic initiatives for the collection, production, and commercialization of grass propagules. Even in regions where seed collector networks exist, grasses are often not prioritized, resulting in poor representation relative to the high diversity and ecological importance of this taxon [122]. Part of this disinterest in collecting and commercializing grass seeds might be due to the high proportion of empty or non-viable seeds [83,132,136,141], which increases the difficulty and cost of obtaining viable material.

Another challenge to obtaining grass seeds for use in restoration of degraded rupes-trian areas is the difficulty of collection. Unlike many tree species from which a large number of seeds can be obtained from a single individual, most grass species produce relatively few seeds per individual and do not always form large, dense population in a single area. This makes collection difficult and substantially increases costs. For example, in seed collection networks in the Cerrado, the price of one kilogram of seeds of *Echinolaena inflexa*—one of the most abundant grasses in that biome and common in rupes-trian grasslands—can be up to ten times higher than the price of widely marketed tree seeds [122]. Despite this high price, *E. inflexa* shows low germination rates (Supplementary Materials Table S2), which reduces its attractiveness for restoration projects. For species with sparser distributions, collection costs and logistical difficulties can be even greater. It is important to emphasize that, in addition to high cost, collection from natural populations must respect ethical and conservation limits. It is recommended that no more than 10% of the available seeds in a population should be removed, so that natural regeneration and population viability are not compromised [144,145].

Given this scenario, there is a clear need to expand studies on the reproductive biology and ecology of Campos Rupestres grasses to support the development of effective techniques for their use in restoration of degraded areas. In this context, recent initiatives aimed at optimizing seed use have been developed, including seedling production [66,141,146,147], vegetative propagation [132,148,149], and micro-propagation [150]. These strategies, detailed in the following sections, are consolidating as promising alternatives (see Table 1 for advantages and disadvantages of different propagation techniques).

However, even with the application of optimized techniques to maximize the use of native grass seeds, it remains necessary to seek ways to increase propagule availability. Beyond difficulties and high costs associated with harvesting from natural populations, suitable collection sites are limited in certain types of Campos Rupestres, such as the ferrug-

inous ones. This limitation arises from the scarcity of accessible areas, restrictions within conservation units, and private land ownership, particularly by mining companies [26].

**Table 1.** Relative comparison of the advantages and disadvantages of different propagation techniques.

| Propagation Method                                                                                            | Financial Cost | Seed Demand | Demand for Propagule Collection or Production | Enables Local Community Integration into the Production Chain | Labor and Specialized Infrastructure Demand | Rate of Degraded Area Coverage and Propagule Dispersal | Suitability for Extremely Inhospitable Areas | Maintenance of Genetic Variability |
|---------------------------------------------------------------------------------------------------------------|----------------|-------------|-----------------------------------------------|---------------------------------------------------------------|---------------------------------------------|--------------------------------------------------------|----------------------------------------------|------------------------------------|
| Direct seeding<br>Seedling or plug<br>Vegetative propagation<br>Rescue and reintroduction<br>Micropropagation | Low            | High        | Yes                                           | Yes                                                           | No                                          | Low                                                    | Low                                          | High                               |
|                                                                                                               | High           | Low         | Yes                                           | Yes                                                           | No                                          | High                                                   | High                                         | High                               |
|                                                                                                               | High           | None        | Yes                                           | Yes                                                           | No                                          | High                                                   | High                                         | Low                                |
|                                                                                                               | Low            | None        | None                                          | No                                                            | No                                          | High                                                   | High                                         | High                               |
|                                                                                                               | High           | None        | Very low                                      | No                                                            | Yes                                         | High                                                   | High                                         | Low                                |

In this context, the commercial production of seeds and seedlings emerges as a strategic alternative. In addition to reducing pressure on natural populations and meeting growing demand, this activity can represent an additional source of income for local communities, integrating them into the ecological restoration process [151] (see Section 6).

5.1. Direct Seeding of Campos Rupestres Grasses in Efforts for the Restoration of Degraded Areas

Although studies remain limited, the use of native grasses from rupestrian grasslands in restoration projects via direct seeding has yielded promising results. This is particularly evident in terms of seedling recruitment and survival across distinct environments, including the Cerrado [116,141–143,152,153]. Among the advantages of direct seeding, reduced labor costs stand out, since this approach eliminates stages associated with seedling production. On the other hand, germination and establishment rates for grasses using this technique tend to be lower than those observed under controlled conditions [116,141,142].

In general, studies involving direct seeding across different taxa report mean establishment rates around 18%. In evaluations conducted with *S. metallicolus*, Figueiredo et al. [66] observed an establishment rate of approximately 58% under controlled conditions at 80 days after sowing, whereas direct seeding in degraded areas yielded only 6% after 12 months [116]. Similarly, Oliveira [141], when assessing four native rupestrian grasses that also occur in the Cerrado (*Aristida riparia*, *Aristida longifolia*, *Loudetiopsis chrysothrix*, and *Schizachyrium sanguineum*), found that for three species the establishment rates under controlled conditions were 4.5 to 25 times higher than those recorded in degraded field conditions.

Considering that direct seeding generally results in lower establishment rates, the use of this technique requires a substantially higher volume of seed per established individual compared to controlled propagation. Thus, its cost–benefit balance must be carefully evaluated, weighing reduced labor costs against increased seed consumption. This aspect is particularly relevant for grasses, whose seeds are usually scarce and expensive to purchase [66,122].

5.2. Seedling and Plug Production of Native Campos Rupestres’ Grasses

As noted in the previous section, establishment rates of native grasses in degraded areas via direct seeding are commonly low. These rates tend to be even lower in severely degraded sites where a large amount of soil has been lost or heavily altered, as in post-mining areas. In these places, the typical environmental filters present in Campos Rupestres (e.g., low water-holding capacity, high solar radiation) become more severe and pose

significant barriers to initial establishment and seedling survival [142,154,155]. For this reason, producing seedlings or plugs under controlled conditions, followed by outplanting into degraded areas represents a promising strategy to optimize seed use, increase survival rates, and accelerate both soil cover and the onset of seed production and dispersal by grasses in restoration sites [66,141,156].

Studies conducted in the Cerrado with species that also occur in Campos Rupestres, such as *Loudetiopsis chrysotrix* and *Schizachyrium sanguineum*, have demonstrated satisfactory results from germination in seedbeds followed by transplanting into containers of different sizes and substrate compositions [146,147]. In degraded areas, survival of these seedlings after transplantation exceeded 79% [141]. Furthermore, for some species, individuals originating from planted seedlings began seed dispersal more quickly than those established by direct seeding, which can favor natural recruitment and the formation of a seed bank in the recovering area [141]. Although promising, the technique of producing individual seedlings has been evaluated for only a limited number of species and needs to be expanded to represent the broad diversity of Campos Rupestres grasses. Oliveira et al. [147] also emphasizes the importance of production-cost analyses to evaluate the feasibility of this technique for restoration practice (see Section 6).

Another method tested to optimize seed use and particularly to enhance establishment in the field is plug production. Figueiredo et al. [66] evaluated this method with *Sporobolus metallicolus*, a grass native to ferruginous and quartzitic Campos Rupestres and recommended for post-mining recovery [157]. In that study, seeds were germinated in trays containing a mixture of substrates and grown for 80 days until they formed a turf (Figure 2A). This turf was then subdivided into 3 × 4 cm plugs (Figure 2B), which were transplanted into post-mined degraded ferruginous Campos Rupestres areas. The results were surprisingly positive, showing 100% plant survival in the field (Figure 2C). Moreover, within only seven months after transplantation, the plants began seed dispersal and increased biomass by approximately 35-fold.



**Figure 2.** (A) *Sporobolus metallicolus* mats produced via seeds and (B) plugs, and (C) growing in the mined area seven months after planting.

Thus, production of seedlings and plugs represents a strategic alternative for restoration of degraded sites, especially for rare species, species with low viable seed production, or species whose seeds are costly. Additionally, this approach can mitigate difficulties related to establishment under extreme edaphic and hydric conditions common in post-mined areas [116,155]. The use of already rooted individuals increases the chances of survival under harsh environmental conditions [141]. Furthermore, planting seedlings

accelerates substrate cover, reducing water and wind erosion as well as colonization by exotic invasive species [156,158].

### 5.3. Vegetative Propagation

Sexual propagation is a major challenge for a large portion of native Campos Rupestres grasses. In the genus *Axonopus*, for example, studies show that of ten evaluated species, six had germination rates below 11%, four did not exceed 5%, and only four species exhibited germination rates above 25% (26–70%, see Figure 1 and Supplementary Materials Table S2). In addition, some species in this genus present more than 80% empty seeds [132,136]. Low germination rates have also been reported for other rupestrian grasses (Figure 1; Supplementary Materials Table S2). In addition to these limitations, some Campos Rupestres grasses do not produce seeds regularly every year and display short periods of seed viability, particularly when stored at ambient temperatures.

On the other hand, several rupestrian grass species present efficient vegetative reproduction, mainly via tillering [119,132,148,149,159]. Vegetative propagation enables rapid production of seedlings ready for transplanting with developed root and shoot systems, which tend to reduce mortality and accelerate vegetation cover in degraded areas. In assessments with *Axonopus laxiflorus* and *Sporobolus metallicolus*, biomass gains relative to the initial biomass of the ramets used to produce the seedlings, reached 75% and 239%, respectively, eight months after propagation [111]. Later evaluations indicated that *A. laxiflorus* seedlings were suitable for field transplantation four months after propagation [160]. Vegetative propagation of *Schizachyrium tenerum* presented 62% survival rate and showed a positive response to nutrient-rich substrates [149]. Matheus et al. [148] evaluated vegetative propagation of five rupestrian grasses (*Axonopus aureus*, *Echinolaena inflexa*, *Loudetiopsis chrysotrix*, *Schizachyrium sanguineum*, and *Trachypogon spicatus*) and observed that *E. inflexa* performed best (40% survival at 150 days), whereas *L. chrysotrix* did not show promising results. The study also revealed that use of a rooting hormone (indolebutyric acid) was detrimental to the rooting process.

Although these studies demonstrate that production of Campos Rupestres's grass seedlings by vegetative propagation is feasible and promising, field evaluations of establishment from these seedlings remain scarce. It is also important to identify morphological and physiological parameters that may serve as indicators of species with greater potential for vegetative propagation [148].

One of the main barriers to large-scale vegetative propagation of grasses is the need to collect donor individuals (clumps or portions thereof) to obtain ramets. To implement this technique without impacting pristine Campos Rupestres areas, it would be necessary to establish specific production areas for ramets. Although production of ramets to supply a potential vegetative propagation chain for native grasses would add additional implementation costs to this method, it could represent an opportunity for income generation for local communities, promoting their integration into the restoration process ([151], see Section 6). Another complementary strategy would be collecting individuals from previously revegetated areas or through rescue operations in areas slated for clearance for new developments.

A relevant concern regarding vegetative propagation is the reduced genetic variability of populations formed through this method. Studies are needed to assess losses of genetic diversity in populations established via vegetative propagation in comparison to natural populations, since vegetative propagation occurs naturally as the main reproductive strategy for many Campos Rupestres grass species [2]. Management strategies should therefore be developed to minimize such potential losses of genetic diversity [132].

Even with limitations related to reduced genetic diversity of populations obtained by vegetative propagation, this method proves to be a valuable tool in restoration projects whose initial focus is the provision of specific ecosystem services, such as erosion control.

The high occurrence of open-pit mining in Campos Rupestres areas, especially ferruginous ones [26], results in extensive areas requiring revegetation for substrate stabilization. This demand has further increased following the enactment of Brazilian Law 14.066/2020, which imposes a series of restrictions on the construction of new tailings dams [161]. Legislative changes regarding dam construction have, in turn, contributed to the greater use of waste rock piles, which also require revegetation.

#### 5.4. Rescue and Reintroduction of Grasses in Campos Rupestres

In Campos Rupestres, particularly in ferruginous sites where mining activity is intense, highly impactful interventions frequently result in total vegetation removal and stripping of the uppermost soil layers. Brazilian legislation requires adoption of mitigation or compensation measures to minimize impacts generated by such projects. Rescue of species in areas where vegetation will be suppressed is often required as a condition for licensing activities and constitutes an important strategy for subsequent restoration actions [162]. Rescue may represent a promising strategy for generating propagules of native species. Although application of this technique is still incipient for grasses in Campos Rupestres, recent studies have demonstrated its feasibility, and authors have proposed management protocols [163,164]. Individuals of *Apochloa molinioides* rescued from a quartzitic Campos Rupestres and later replanted in a degraded area presented survival rates above 90%, demonstrating the potential of this technique for conservation of native grasses and for restoration of degraded areas [163].

Several advantages are associated with the use of rescued individuals. Among these are reduced procurement costs, since commercial material is not required, as well as the adaptability of individuals when reintroduced near the rescue site [165]. In areas that have been previously licensed for mining and other activities that require the removal of vegetation and that harbor rare, endemic, or threatened species, rescue, and reintroduction of individuals into suitable sites is an important conservation strategy [150]. This practice contributes to biodiversity conservation, the maintenance of environmental services, and the ecological interactions associated with these species.

## 6. Potential Ecological Impacts of Depending on Seed Collection in Natural Areas

In the Campos Rupestres, the high proportion of nonviable or embryoless seeds, more than the production of dormant seeds [166], could represent a relevant bottleneck for large-scale seedling production [66,151,167]. Due to the natural microtopographic characteristics of Campos Rupestres, with shallow soils concentrated in small depressions or cracks [168], the seed banks are not an abundant resource in the ecosystem and the persistence for longer than one year seems to be mostly composed of the very small seeded species [166]. Thus, removing seeds both directly from the mother plants and from the seed bank in reference areas, especially at large scales or repeatedly, will reduce the already limited high-quality seed reserves, with negative reflexes on local populations, genetic diversity, potentially hindering the conservation, ecosystem resilience and natural regeneration after disturbances [151,155].

To avoid the impacts of overharvesting seeds from natural populations and to balance restoration needs with ecosystem conservation, technical solutions that guarantee the supply ex situ of seeds and vegetative structures capable of producing seedlings must be sought [144,145]. Designating degraded areas for the cultivation of native grasses, for

example, could offer multiple advantages. In addition to restoring the functions performed by native grasses to the site [67,169], the grass community would be a constant source of seeds and bud matrixes. The well-planned collection of these resources in the area, and eventual enrichments with new matrices derived from recovery from mining areas, or from the exchange of seeds with other Campo Rupestre native grass producers, could guarantee genetic diversity, a very important requisite for restoration ecology [144]. These practices would foster networks of local and regional producers of native plants, bringing a source of income based on the sustainable exploitation of natural resources beyond collecting seeds in natural areas ([170], see more about the grass market in the following topic). While seed collection networks are growing in importance in Brazil [171], native grass seed producers are not yet a reality.

## 7. Seedling Production Costs and Market for Native Grass Seeds from Campos Rupestres

Recent research demonstrates that propagation of *Sporobolus metallicolus* via seeds is technically feasible and can be achieved at low cost [66]. Sods of the grass were produced using a mixture of bauxite post-mining substrate and commercial soil. About eighty days after sowing, the mats were divided into 3 × 4 cm plugs, each one containing, on average, 11 individuals that formed a stable and well-rooted soil volume. The plugs were later planted in an area degraded by bauxite mining, showing 100% establishment and good further development. The cost estimate encompassed the time required for seed collection in reference areas, seed processing in the laboratory, sowing and seedling growing, substrate collection in the post-mined area and its transportation to the seedling production site, as well as the costs associated with the purchase of 1 m<sup>3</sup> of commercial planting substrate, and the use of irrigation water. This system yielded plug-plants at an estimated cost of US\$ 0.0045 per unit, which is considerably lower than the average price of producing tropical forest and savanna tree seedlings (US\$ 0.64, [172]). In comparison, a study of direct seeding of *S. metallicolus* in a post-mining area estimated a cost of US\$ 0.09 per plant established after 12 months, including substrate preparation [116]. Despite higher input and labor demands, seedling and plug production substantially reduce seed loss, a relevant point to be considered given the high cost of seeds. In the study by Figueiredo et al. [66], the cost per kilogram of *S. metallicolus* seed (including impurities) was estimated at US\$ 69.10, considering only collection and basic processing. In another assessment, seeds of *Echinolaena inflexa* reached prices near US\$ 103/kg [122].

The cost-effectiveness ratio might be improved at various stages of the seedling production process, especially when considering expanding the production scale, but technical alternatives need to be tested and very well balanced. For example, viable grass seeds can be easily separated from non-viable ones via flotation, which ensures a higher germination rate [138]. Studies have demonstrated that this method is also suitable for seeds of other species, including the woody ones from Campo Rupestre and Cerrado ecosystems [146,147,167], increasing the efficiency of producing individual seedlings via seeds. Conversely, when the primary objective is the rapid establishment of vegetation cover per unit area (e.g., mats or plugs), the expenses associated with seed separation and drying, in addition to the required materials, may outweigh the potential benefits, suggesting that streamlined propagation methods could be more cost-effective in such contexts. As established for direct seeding, to reduce the time effort of separating viable seeds, preliminary studies of the proportion of viable seeds per unit weight determine the seed mass collected that contains a desirable number of viable seeds. This significantly reduces the cost of seed processing [116,142]. Similarly, using substrate from the post-mined area not only lowers costs and reduces pressure on organic soils but also fosters seedlings

with roots and physiology pre-adapted to the edaphic conditions of the restoration site. On the other hand, depending on the required substrate volume and the logistics of collection and transportation distance to the seedling production area, this may not be the best strategy. In fact, costs will vary greatly depending on distances to seed donor areas, substrate type, size of growing containers, the need for fertilizers or amendments [146,147,173]. In comparison, direct seeding and hay transfer methods are less expensive per hectare but may have lower establishment rates [66,172,174].

To the best of our knowledge, no other study quantifying the costs of producing seedlings of native grasses from Campos Rupestres or from other open grassy ecosystem, have been published, which reflects the still underdeveloped market for native grass seedlings and seeds in Brazil. In the Pampas biome region, Southern Brazil, the natural grasslands in the highlands presents one of the greatest diversities of herbaceous species per area, 20 to 35 species/m<sup>2</sup> on average [175]. Despite this and the enormous demand for restoration of degraded Pampa areas, only a handful of native species seedlings suppliers were found [176]. In the nurseries, only seven native species were available commercially, including four grasses (*Aristida jubata*, *Coleataenia prionitis*, *Cortaderia selloana* and *Paspalum notatum*). They also found seeds of two native grass species available on internet pages of seed sellers (*Axonopus affinis* and *A. compressus*). Notably, the cultivation of seedlings and commercialization of native grass seeds from other open and highly diverse ecosystems, such as the Cerrado and Campos Rupestres, face similar or even greater constraints. Savannic and grasslands phytophysionomies cover about 70% of the Cerrado [177], with herbaceous species as the predominant life form.

The more established seed supply systems in *cerrado* region trade seeds of 263 species, of which 68% are trees. Among the Poaceae, seeds of 19 species from the genus *Andropogon* (3 species), *Aristida* (4), *Axonopus* (3), *Paspalum* (2), and the species *Ctenium cirrosum*, *Echinolaena inflexa*, *Gymnopogon foliosus*, *Hyparrhenia bracteata*, *Loudetiopsis chrysothrix*, *Schizachyrium sanguineum* and *Sorghastrum setosum* are found for sale [122]. Although some of these species also occur in Campos Rupestres, no seed sellers were found in regions where these ecosystems predominate, such as Minas Gerais and Bahia Brazilian States. This absence clashes with the enormous demand for the effective restoration of Campo Rupestre areas degraded by mining. Although the total area affected by iron ore production is not disclosed, it has grown vigorously in recent years. The value of Brazilian mineral production in 2024 increased approximately 9.1% compared to 2023 and was led by iron ore, responsible for 59.3% of the total produced [178].

According to the Custom Market Insights (CMI, [179]), the global native grass seeds market is projected to reach USD 24.58 billion by 2033, being the land conservation and rehabilitation segment a main driver due to the increasing focus on ecological restoration and sustainable practices. Projections suggest that large-scale restoration decade targets in Brazil could require thousands of tonnes of native seeds, with the potential to generate about US\$ 36.9 million per year of income for seed producers [180]. Community-based seed networks and local initiatives are emerging as key players in both scaling up supply and delivering socioeconomic benefits [170,171,181]; however, the lack of legal requirements for grassland restoration and limited policy support have hindered market development [176,182,183]. Current regulations are often restrictive, requiring costly technical documentation and limiting the trade of seed mixtures, which impedes the development of a robust supply chain [182,183]. The absence of clear legal requirements for grassland restoration, as opposed to forest restoration, further limits market growth [176,183]. Recommendations include adapting regulations to local contexts, streamlining seed quality assurance, and providing government incentives to stimulate production and commercialization [181–183]. As pointed out by Nevill et al. [184], a strong business model for the cultivation of na-

tive species seeds can emerge, combining ecology and economy, but first our perception of the recovery of degraded areas needs to evolve from purely corrective actions to an economic opportunity.

Scaling up native grass production for ecological restoration requires coherent policy frameworks that stimulate local enterprise, ensure genetic provenance, and secure community participation. Governments should establish targeted incentives, such as grants, tax relief, and public procurement quotas, to guarantee consistent demand for native seeds. Adapted seed regulations are also essential, allowing community producers simplified certification and quality assurance pathways appropriate for non-commodity native species. Public investment in regional seed labs, storage, and processing infrastructure can reduce logistical barriers and enable small producers to meet restoration needs. Integrating native seed use into national restoration programs and payment for ecosystem services (PES) schemes ensure financial flows directly benefit community producers while advancing biodiversity and climate commitments [181,185].

The establishment of Seed Production Areas (SPAs) and nucleus farms is central to ensuring reliable, high-quality seed supply. These areas should be located in ecologically suitable regions to facilitate the multiplication of locally adapted genotypes and allow consistent, large-scale harvests. SPAs also serve as training and demonstration hubs, linking research institutions, extension services, and community enterprises [186].

At the community level, success depends on empowering local actors through co-operatives, social enterprises, and benefit-sharing arrangements. Supporting community governance, providing business and technical training, and recognizing Indigenous and local knowledge are critical for equitable participation. Inclusive planning, particularly ensuring women's involvement, enhances social outcomes and long-term stewardship [187]. Together, these measures create an enabling environment where community-based production networks can supply large-scale restoration efforts while fostering rural livelihoods and biodiversity conservation [170].

## 8. Research Gaps

Despite advances in understanding the grass diversity, seed germination, and seedling production in Campos Rupestres, critical knowledge gaps remain that must be addressed to strengthen conservation and restoration approaches based on native grasses. Undoubtedly, as data collected in the literature have demonstrated (see Section 4.1), much of the botanical material collected in the field remains identified only by family, suggesting an enormous demand for the training of taxonomists dedicated to Poaceae. Moreover, information on seed viability, dormancy, germination, and dispersal of a high number of native grass species is still limited. Moreover, the effectiveness of restoration techniques must be assessed over extended spatial and temporal scales, as the limited dispersal capacity and slow growth rates of native species may restrict restoration success. Understanding how morphological and physiological traits of native grass species influence ecological processes in Campos Rupestres remain deficient, limiting the ability to optimize functional outcomes. Although methods such as seedling production, topsoil transposition, and the use of post-mining substrates show promising results, comparative assessments of cost-effectiveness, long-term ecological outcomes, and large-scale feasibility remain insufficient. The absence of specific policies for the restoration of grass-dominated ecosystems and regulatory barriers limit the development of seed and seedling production chains for native grasses.

In summary, advancing restoration in Campos Rupestres requires integrative studies on reproductive biology, functional ecology, and long-term performance of grasses, coupled with the development of scalable propagation techniques and supportive policy frameworks. Bridging these gaps will enable the use of native grasses as cornerstone species for

restoring biodiversity and ecosystem functionality in one of the world's most threatened megadiverse ecosystems.

## 9. Conclusions

Native grasses are fundamental to the structure and functioning of Campos Rupestres but remain underrepresented in restoration practice. This review highlights that propagation knowledge is still limited to a small subset of species and that strong interspecific variation in seed viability, dormancy, and establishment constrains large-scale use. Seedling, plug, vegetative propagation, and rescue approaches show clear potential to improve establishment and reduce seed demand, yet their effectiveness is rarely validated under field conditions.

Priority research should focus on (i) field-scale validation of propagation techniques across degradation gradients, (ii) assessment of genetic diversity implications of different propagation strategies, and (iii) development of scalable ex situ seed and seedling production systems to ensure a reliable supply of native grasses without further pressure on natural populations. Addressing these priorities is essential to integrate native grasses as core components of restoration strategies in Campos Rupestres.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/grasses5010004/s1>. Table S1: A checklist compiled from herbarium databases and scientific publications. Table S2: Relevant supplementary information is organized in the Excel file. The spreadsheet "Data" summarizes the mean values obtained from germination experiments with grass species from Campos Rupestres. As an inclusion criterion, we considered studies that evaluated the germination of native grasses from Campos Rupestres, even when the seeds used in the experiments had not been collected directly in areas from Campos Rupestres. Germination values preceded by \* indicate that the number represents an approximate germination percentage, as the data were originally presented in graphical form. In the column referring to the experimental temperature, when four numbers are provided, they indicate that the experiment was conducted under alternating temperatures. The first two numbers represent the temperatures used, and the subsequent two numbers represent, respectively, the duration (in hours) at which each temperature was applied each day. In the column referring to light conditions, the values following the letters "L" and "D" represent the number of hours with and without light, respectively. The column Seed selection indicates whether seeds were selected prior to the germination experiments, including the removal of empty or damaged seeds. N.A.—Information not available. The full references of the studies cited in the spreadsheet are listed in the reference section of the article [188–196].

**Author Contributions:** All authors contributed equally to the conceptualization, data collection, writing of the original draft preparation, and review and editing and have read and agreed to the published version of the manuscript. All authors have read and agreed to the published version of the manuscript.

**Funding:** Part of the data presented in this review was derived from the APQ-00724-22 project, funded by the Research Support Foundation of Minas Gerais State (FAPEMIG).

**Data Availability Statement:** The original contributions presented in this study are included in the Supplementary Materials. Further inquiries can be directed to the corresponding authors.

**Acknowledgments:** The authors would like to thank Mariangela G. P. Leite, Geology Department, UFOP, for her kind review of the text in Section 2 and Paul Digney for the English review. During the preparation of this manuscript, the authors used Google Gemini for the purpose of reviewing the grammar and clarity of certain parts of the text. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Zappi, D.C.; Moro, M.F.; Meagher, T.R.; Nic Lughadha, E. Plant Biodiversity Drivers in Brazilian Campos Rupestres: Insights from Phylogenetic Structure. *Front. Plant Sci.* **2017**, *8*, 2141. [CrossRef]
2. Silveira, F.A.O.; Negreiros, D.; Barbosa, N.P.U.; Buisson, E.; Carmo, F.F.; Cartensen, D.W.; Conceição, A.A.; Cornelissen, T.G.; Echternacht, L.; Fernandes, G.W.; et al. Ecology and evolution of plant diversity in the endangered campo rupestre: A neglected conservation priority. *Plant Soil* **2016**, *403*, 129–152. [CrossRef]
3. Echternacht, L.; Souto, D.; Silva, L.; de Lima, T.; Ramos, R. *Comanthera gandarela*, a critically endangered new species from the ferruginous campos rupestres (Cangas) of Serra do Gandarela, Minas Gerais, Brazil (Eriocaulaceae). *Phytotaxa* **2025**, *726*, 20–36. [CrossRef]
4. Fernandes, G.W.; Barbosa, N.P.U.; Alberton, B.; Barbieri, A.; Dirzo, R.; Goulart, F.; Guerra, T.J.; Morellato, L.P.C.; Solar, R.R.C. The deadly route to collapse and the uncertain fate of Brazilian rupestrian grasslands. *Biodivers. Conserv.* **2018**, *27*, 2587–2603. [CrossRef]
5. Rocha, L.H.; Gonella, P.M.; Andrino, C.O. A missing piece is found: A new species of *Paepalanthus* (Poales, Eriocaulaceae) and the puzzling relations of the campos rupestres mountaintop floras of eastern Minas Gerais, Brazil. *PhytoKeys* **2024**, *242*, 317–332. [CrossRef]
6. Santos, M.T.T.; Pinheiro, P.D.P.; Garcia, P.C.A.; Griffiths, R.A.; Haddad, C.F.B.; Barata, I.M. A new species of *Crossodactylodes* from the Espinhaço Mountain Range, Southeastern Brazil (Anura: Leptodactylidae: Paratelmatobiinae). *Herpetologica* **2023**, *79*, 108–118. [CrossRef]
7. Cabral, A.; Magri, R.A.; Lopes, J.C. Increasing knowledge on the diversity of canelas-de-ema in the campo rupestre: Two new species of *Vellozia* (Velloziaceae) from the southern Espinhaço Range, Brazil. *Plant Ecol. Evol.* **2022**, *155*, 343–352. [CrossRef]
8. Lima, L.L.; Kozovits, A.R.; Magna, D.A.A.; Silva, G.A.; Oehl, F. *Cetraspora auronigra*, a new glomeromycete species from Ouro Preto (Minas Gerais, Brazil). *Sydowia* **2014**, *66*, 299–308. [CrossRef]
9. Fernandes, G.W. The megadiverse rupestrian grassland. In *Ecology and Conservation of Mountaintop Grasslands in Brazil*, 1st ed.; Fernandes, G.W., Ed.; Springer: Cham, Switzerland, 2016; pp. 3–14.
10. Oliveira, R.S.; Abrahão, A.; Pereira, C.; Teodoro, G.S.; Brum, M.; Alcantara, S.; Lambers, H. Ecophysiology of Campos Rupestres Plants. In *Ecology and Conservation of Mountaintop Grasslands in Brazil*, 1st ed.; Fernandes, G., Ed.; Springer: Cham, Switzerland, 2016; pp. 227–272.
11. Fernandes, G.W.; Arantes-Garcia, L.; Barbosa, M.; Barbosa, N.P.U.; Batista, E.K.L.; Beiroz, W.; Wallace Beiroz, W.; Resende, F.M.; Abrahão, A.; Almada, E.D.; et al. Biodiversity and ecosystem services in the campo rupestre: A road map for the sustainability of the hottest Brazilian biodiversity hotspot. *Perspect. Ecol. Conserv.* **2020**, *18*, 213–222. [CrossRef]
12. Diniz, J.M.F.S.; Reis, A.A.; Júnior, F.W.A.; Gomide, L.R. Detecção da expansão da área minerada no quadrilátero ferrífero, minas gerais, no período de 1985 a 2011 através de técnicas de sensoriamento remoto. *Bol. Ciências Geodésicas* **2014**, *20*, 683–700. [CrossRef]
13. de Azevedo, M.L.; Sperandio, H.V.; Coelho, F.A.; Silva, R.; Gorgens, E. Assessment climate change impacts on a key species of campos rupestres: Can we preserve the everlasting flower? *Plant Ecol.* **2025**, *226*, 587–601. [CrossRef]
14. Bugado, R.E.; Shrestha, N.; Magri, R.A.; Prado, J.; Lopes, J.C. Vanishing ecosystems: The looming threat of climate change on an iconic genus *Vellozia* in the Brazilian campos rupestres. *Glob. Ecol. Conserv.* **2025**, *58*, e03439. [CrossRef]
15. Moreira, P.A.; Pires, A.; Beirão, M.V. An Announced Extinction: The Impacts of Mining on the Persistence of *Arthrocreus glaziovii*, a Microendemic Species of Campos Rupestres. *Conservation* **2024**, *4*, 50–162. [CrossRef]
16. Macedo, C.R.; Marcelino, R.A.G.; Amaral e Silva, A.; Lorentz, J.F.; de Assis, L.R.; dos Santos, V.J.; Calijuri, M.L. The influence of mining in the Quadrilátero Ferrífero: Landscape spatial-temporal dynamics. *J. Hyperspectr. Remote Sens.* **2021**, *11*, 96–112. [CrossRef]
17. Flora e Funga do Brasil. Jardim Botânico do Rio de Janeiro. 2025. Available online: <https://floradobrasil.jbrj.gov.br/consulta/#CondicaoTaxonCP> (accessed on 30 November 2025).
18. Specieslink Network. 2025. Available online: <https://specieslink.net/> (accessed on 30 November 2025).
19. Viana, P.L.; Filgueiras, T.S. Inventário e distribuição geográfica das gramíneas (Poaceae) na Cadeia do Espinhaço, Brasil. *Megadiversidade* **2008**, *4*, 99–116.
20. Vinícius-Silva, R.; Paula, C.; Saraiva, D. New records of *Gymnopogon doellii* (Poaceae, Chloridoideae, Cynodonteae, Hubbardochoinae), a Brazilian endangered species. *Phytotaxa* **2020**, *435*, 57–62. [CrossRef]
21. Garcia, R.J.F.; Longhi-Wagner, H.M.; Pirani, J.R.; Meirelles, S.T. A contribution to the phytogeography of Brazilian campos: An analysis based on Poaceae. *Braz. J. Bot.* **2009**, *32*, 703–713. [CrossRef]
22. Hopper, S. OCBIL theory: Towards an integrated understanding of the evolution, ecology and conservation of biodiversity on old, climatically buffered, infertile landscapes. *Plant Soil* **2009**, *322*, 49–86. [CrossRef]
23. Lambers, H.; Raven, J.A.; Shaver, G.R.; Smith, S.E. Plant nutrient-acquisition strategies change with soil age. *Trends Ecol. Evol.* **2008**, *23*, 96–103. [CrossRef]

24. Lambers, H.; Brundrett, M.C.; Raven, J.A.; Hopper, S.D. Plant mineral nutrition in ancient landscapes: High plant species diversity on infertile soils is linked to functional diversity for nutritional strategies. *Plant Soil* **2010**, *334*, 11–31. [[CrossRef](#)]
25. Hopper, S.D.; Silveira, F.A.O.; Fiedler, P.L. Biodiversity hotspots and Ocbil theory. *Plant Soil* **2016**, *403*, 167–216. [[CrossRef](#)]
26. Fernandes, G.W.; Barbosa, N.P.U.; Negreiros, D.; Paglia, A.P. Challenges for the conservation of vanishing megadiverse rupestrian grasslands. *Nat. Conserv.* **2014**, *12*, 162–165. [[CrossRef](#)]
27. Viana, P.L.; Lombardi, J.A. Florística e caracterização dos campos rupestres sobre canga na serra da Calçada, Minas Gerais, Brasil. *Rodriguésia* **2007**, *58*, 159–177. [[CrossRef](#)]
28. Jacobi, C.M.; Carmo, F.F. Diversidade dos campos rupestres ferruginosos no Quadrilátero Ferrífero, MG. *Megadiversidade* **2008**, *4*, 25–33.
29. Lamounier, W.L.; Carvalho, V.L.M.; Salgado, A.A.R. Serra do Gandarela: Possibilidade de ampliação das unidades de conservação no Quadrilátero Ferrífero-MG. *Rev. Dep. Geogr.* **2011**, *22*, 171–192. [[CrossRef](#)]
30. Azevedo, U.R.; Machado, M.M.M.; Castro, P.T.A.; Renger, F.E.; Trevisol, A.; Beato, D.A.C. Geoparque Quadrilátero Ferrífero (MG): Proposta. In *Geoparques do Brasil: Propostas*, 1st ed.; Schobbenhaus, C., Silva, C.R., Eds.; CPRM: Brasília, Brazil, 2012; Volume 1, Chapter 7, pp. 183–220. Available online: [https://rigeo.sgb.gov.br/bitstream/doc/1209/1/geoparques\\_brasil\\_propostas.pdf](https://rigeo.sgb.gov.br/bitstream/doc/1209/1/geoparques_brasil_propostas.pdf) (accessed on 20 October 2025).
31. Ferreira, D.A.; Leite, M.G.P.; Messias, M.C.T.B.; Fujaco, M.A.G.; Marques, E.D.; Gaião, L.M.; Kozovits, A.R. Spatial distribution and geochemical background of quartzitic and ferruginous rupestrian field soils. *Catena* **2024**, *246*, 108369. [[CrossRef](#)]
32. Giulietti, A.M.; Pirani, J.R.; Harley, R.M. Espinhaço range region eastern Brazil. In *Centres of Plant Diversity: A Guide and Strategy for Their Conservation*, 1st ed.; Davis, S.D., Heywood, V.H., Eds.; World Wide Fund for Nature/World Conservation Union: Cambridge, UK, 1997; Volume 3, pp. 397–404.
33. Giulietti, A.M.; Harley, R.; Queiroz, L.; Wanderley, M.G.L.; Pirani, J.R. Caracterização e endemismos nos campos rupestres da Cadeia do Espinhaço. In *Tópicos Atuais em Botânica*, 1st ed.; Cavalcanti, T.B., Walter, B.T.M., Eds.; SBB/Embrapa: Brasília, Brazil, 2000; pp. 311–318.
34. Gonçalves, T.; Silva, A.; Filho, C.; Costa, C.; Braga, I. Origin and phytogeographic evolution of the Rupestrian Fields of the Espinhaço Chain. *Int. J. Geosci. Eng. Technol.* **2020**, *1*, 63–68. [[CrossRef](#)]
35. Conceição, A.; Pirani, J.R. Delimitação de habitats em campos rupestres na Chapada Diamantina, Bahia: Substratos, composição florística e aspectos estruturais. *Bol. Bot. Univ. São Paulo* **2005**, *23*, 85–111. [[CrossRef](#)]
36. Neves, S.; Conceição, A. Vegetação em afloramentos rochosos na Serra do Sincorá, Chapada Diamantina, Bahia, Brasil. *Sitientibus Sér. Ciências Biol.* **2007**, *7*, 36–45. [[CrossRef](#)]
37. Silva, M.F.F.; Secco, R.S.; Lobo, M.G. Ecological Aspects of the Tropical Scrub Vegetation on Rocky Outcrops of the Serra dos Carajás, State of Pará, Brazil. *Acta Amaz.* **1996**, *26*, 17–44. [[CrossRef](#)]
38. Pereira, J.B.S.; Arruda, A.J.; Salino, A. Flora of the cangas of Serra dos Carajás, Pará, Brazil: Isoetaceae. *Rodriguésia* **2017**, *68*, 853–857. [[CrossRef](#)]
39. de Oliveira Mota, N.F.; Watanabe, M.T.C.; Zappi, D.C.; Hiura, A.L.; Pallos, J.; Viveros, R.S.; Giulietti, A.M.; Viana, P.L. Amazon canga: The unique vegetation of Carajás revealed by the list of seed plants. *Rodriguésia* **2018**, *69*, 1435–1488. [[CrossRef](#)]
40. Almeida, F.F.M.; Hasui, Y.; de Brito Neves, B.B.; Fuck, R.A. Brazilian structural provinces: An introduction. *Earth Sci. Rev.* **1981**, *17*, 1–29. [[CrossRef](#)]
41. Bizzi, L.A.; Schobbenhaus, C.; Vidotti, R.M.; Gonçalves, J.H. *Geologia, Tectônica e Recursos Minerais do Brasil*, 1st ed.; CPRM: Brasília, Brazil, 2003. Available online: [https://rigeo.sgb.gov.br/jspui/bitstream/doc/5006/2/geologia\\_tectonica.pdf](https://rigeo.sgb.gov.br/jspui/bitstream/doc/5006/2/geologia_tectonica.pdf) (accessed on 20 October 2025).
42. Schaefer, C.; Corrêa, G.; Galvão Candido, H.; Arruda, D.; Nunes, J.; Araujo, R. The Physical Environment of Rupestrian Grasslands (Campos Rupestres) in Brazil: Geological, Geomorphological and Pedological Characteristics, and Interplays. In *Ecology and Conservation of Mountaintop Grasslands in Brazil*, 1st ed.; Fernandes, G., Ed.; Springer: Cham, Switzerland, 2016; pp. 15–53.
43. Riccomini, C.; Assumpção, M. Quaternary tectonics in Brazil. *Epis. J. Int. Geosci.* **1999**, *22*, 221–225. [[CrossRef](#)]
44. Benites, V.M.; Schaefer, C.E.G.R.; Simas, F.N.B.; Santos, H.G. Soils associated with rock outcrops in the Brazilian mountain ranges Mantiqueira and Espinhaço. *Rev. Bras. Bot.* **2007**, *30*, 569–577. [[CrossRef](#)]
45. Miola, D.; Ramos, V.; Silveira, F. A brief history of research in campo rupestre: Identifying research priorities and revisiting the geographical distribution of an ancient, widespread neotropical biome. *Biol. J. Linn. Soc.* **2021**, *133*, 464–480. [[CrossRef](#)]
46. Queiroz, R.; Souza, B.; Souza, J.; Medeiros, J.; Fonseca, C.; Cardoso, E. Extending the limits of campos rupestres in Brazil. *Caminhos Geogr.* **2021**, *22*, 115–137. [[CrossRef](#)]
47. Streit, H.; Bergamin, R.S.; Andrade, B.O.; Altesor, A.; Lezama, F.; Perelman, S.; Müller, S.C.; Overbeck, G.E. Determinants of biogeographical distribution of grasses in grasslands of South America Perspect. *Plant Ecol. Evol. Syst.* **2024**, *63*, 125791. [[CrossRef](#)]
48. Thomas, P.; Schüller, J.; Boavista, L.; Torchelsen, F.; Overbeck, G.; Müller, S. Controlling the invader *Urochloa decumbens*: Subsidies for ecological restoration in subtropical campos grassland. *Appl. Veg. Sci.* **2018**, *22*, 96–104. [[CrossRef](#)]

49. Gastauer, M.; Messias, M.C.T.B.; Meira Neto, J.A.A. Floristic composition, species richness and diversity of campo rupestre vegetation from the Itacolomi State Park, Minas Gerais, Brazil. *Environ. Nat. Resour. Res.* **2012**, *2*, 115–128. [\[CrossRef\]](#)
50. Messias, M.C.T.B.; Leite, M.G.P.; Meira Neto, J.A.A.; Kozovits, A.R. Life-form spectra of quartzite and itabirite rocky outcrop sites, Minas Gerais, Brazil. *Biota Neotrop.* **2011**, *11*, 255–268. [\[CrossRef\]](#)
51. Messias, M.C.T.B.; Leite, M.G.P.L.; Meira-neto, J.A.A.; Kozovits, A.R. Fitossociologia de campos rupestres quartzíticos e ferruginosos no Quadrilátero Ferrífero, Minas Gerais. *Acta Bot. Bras.* **2012**, *26*, 230–242. [\[CrossRef\]](#)
52. Carmo, F.F.; Jacobi, C.M. A vegetação de canga no Quadrilátero Ferrífero, Minas Gerais: Caracterização e contexto fitogeográfico. *Rodriguésia* **2013**, *64*, 527–541. [\[CrossRef\]](#)
53. de Carvalho, F.; Godoy, E.L.; Lisboa, F.J.G.; de Souza Moreira, F.M.; de Souza, F.A.; Berbara, R.L.L.; Fernandes, G.W. Relationship between physical and chemical soil attributes and plant species diversity in tropical mountain ecosystems from Brazil. *J. Mt. Sci.* **2014**, *11*, 875–883. [\[CrossRef\]](#)
54. Silva, T.C. Florística e Fitossociologia de um Campo Rupestre Ferruginoso na APA Estadual da Cachoeira das Andorinhas, Ouro Preto, MG. Bachelor's Thesis in Biology, Federal University of Ouro Preto, Ouro Preto, Brazil, 2014.
55. Takahasi, A. Flora das cangas de Corumbá, MS: Diversidade e conservação. In *Geossistemas Ferruginosos do Brasil: Áreas Prioritárias para Conservação da Diversidade Geológica e Biológica, Patrimônio Cultural e Serviços Ambientais*, 1st ed.; do Carmo, F.F., Kamino, L.H.Y., Eds.; 3I Editora: Belo Horizonte, Brazil, 2015; pp. 317–334.
56. Mota, N.F.d.e.; Silva, L.V.C.; Martins, F.D.; Viana, P.L. Vegetação sobre sistemas ferruginosos da Serra dos Carajás. In *Geossistemas Ferruginosos do Brasil: Áreas Prioritárias para Conservação da Diversidade Geológica e Biológica, Patrimônio Cultural e Serviços Ambientais*; do Carmo, F.F., Kamino, L.H.Y., Eds.; 3I Editora: Belo Horizonte, Brazil, 2015; pp. 289–316.
57. Conceição, A.A.; Pirani, J.R.; Meirelles, S.T. Floristics, structure and soil of insular vegetation in four quartzite-sandstone outcrops of Chapada Diamantina Northeast Brazil. *Rev. Bras. Bot.* **2007**, *3*, 641–656. [\[CrossRef\]](#)
58. Mourão, A.; Stehmann, J.R. Floristic inventory of the remaining Campo Rupestre over hematitic litholic canga at the Brucutu Mine, Barão de Cocais, Minas Gerais, Brazil. *Rodriguésia* **2007**, *58*, 775–786. [\[CrossRef\]](#)
59. Jacobi, C.M.; Flávio, F.; Vincent, R.C.; Stehmann, J.R. Plant communities on ironstone outcrops: A diverse and endangered Brazilian ecosystem. *Biodivers. Conserv.* **2007**, *16*, 2185–2200. [\[CrossRef\]](#)
60. Scalon, V.R.; Leandro, C.M.; Cândido, E.S. Florística dos remanescentes de campo rupestre sobre canga no Campus Morro do Cruzeiro/UFOP, Ouro Preto, Minas Gerais, Brasil. *MG Biota* **2012**, *5*, 19–47.
61. Messias, M.C.T.B.; Tonaco, A.C.; Meira Neto, J.A.A.; Leite, M.G.P. Levantamento florístico de um campo rupestre ferruginoso na Serra de Antônio Pereira, Ouro Preto, Minas Gerais. *MG Biota* **2012**, *5*, 4–18.
62. Messias, M.C.T.B.; Leite, M.G.P.; Meira Neto, J.A.A.; Kozovits, A.R. Soil-vegetation relationship in quartzitic and ferruginous Brazilian rocky outcrops. *Folia Geobot.* **2013**, *48*, 509–521. [\[CrossRef\]](#)
63. Cardoso, R.C. Florística e Fitossociologia de um Campo Rupestre Quartzítico na Área de Proteção Ambiental Estadual da Cachoeira das Andorinhas, Ouro Preto, MG. Bachelor's Thesis in Biology, Federal University of Ouro Preto, Ouro Preto, Brazil, 2013.
64. Messias, M.C.T.B.; Carmo, F.F. Flora e vegetação em substratos ferruginosos do sudeste do Quadrilátero Ferrífero. In *Geossistemas Ferruginosos do Brasil: Áreas Prioritárias para Conservação da Diversidade Geológica e Biológica, Patrimônio Cultural e Serviços Ambientais*, 1st ed.; do Carmo, F.F., Kamino, L.H.Y., Eds.; 3I Editora: Belo Horizonte, Brazil, 2015; pp. 335–360.
65. Oliveira, P.A.; Pereira, I.M.; Messias, M.C.T.B.; Romarce, M.L.; Pinheiro, A.C.; Machado, E.L.M.; Alves, J.L. Phytosociology of the herbaceous-subshrub layer of a rupestrian complex in Serra do Espinhaço, Brazil. *Acta Bot. Bras.* **2018**, *32*, 141–149. [\[CrossRef\]](#)
66. Figueiredo, M.; Messias, M.C.T.B.; Leite, M.G.P.; Kozovits, A.R. Native grass sod and plug production as an alternative technique to restore neotropical rupestrian grassland after mining. *Restor. Ecol.* **2023**, *31*, e13966. [\[CrossRef\]](#)
67. Rocha, F.C.G.; Oliveira, F.S.; Leite, M.G.P.; Dias, D.D.; Messias, M.C.T.B.; Kozovits, A.R. Chemical and microstructural behaviour of ferruginous rocky outcrops topsoils applied to degraded mining areas. *Int. J. Min. Reclam. Environ.* **2020**, *35*, 219–234. [\[CrossRef\]](#)
68. Nerlekar, A.; Spalink, D.; Veldman, J. Grass functional traits reflect the long history of fire and grazers in the savannas of Texas. *Am. J. Bot.* **2025**, *112*, e70013. [\[CrossRef\]](#)
69. Elliott, T.L.; Spalink, D.; Larridon, I.; Zuntini, A.R.; Escudero, M.; Hackel, J.; Barrett, R.L.; Martín-Bravo, S.; Márquez-Corro, J.I.; Granados Mendoza, C.; et al. Global analysis of Poales diversification—Parallel evolution in space and time into open and closed habitats. *New Phytol.* **2024**, *242*, 727–743. [\[CrossRef\]](#)
70. Linder, H.; Lehmann, C.; Archibald, S.; Osborne, C.; Richardson, D. Global grass (Poaceae) success underpinned by traits facilitating colonization, persistence and habitat transformation. *Biol. Rev.* **2018**, *93*, 1125–1144. [\[CrossRef\]](#)
71. Figueiredo, M.A.; Messias, M.C.T.B.; Leite, M.G.P.; Kozovits, A.R. Topsoil volume optimization in the restoration of post-mined areas. *Restor. Ecol.* **2024**, *32*, e14222. [\[CrossRef\]](#)
72. Saraiva, D.F.; Botelho, S.A.; Paula, C.C.; Vinícius-Silva, R.; Moraes, P.J.; Melo, L.A. Gramíneas nativas potenciais para revegetação de áreas degradadas, a partir da avaliação de topsoil de campo rupestre ferruginoso. *Hoehnea* **2020**, *47*, e1122019. [\[CrossRef\]](#)

73. Onésimo, C.M.G.; Dias, D.D.; Vale Beirão, M.; Kozovits, A.R.; Messias, M.C.T.B. Ecological succession in areas degraded by bauxite mining indicates successful use of topsoil. *Restor. Ecol.* **2021**, *29*, e13303. [\[CrossRef\]](#)
74. IUCN. The IUCN Red List of Threatened Species. Version 2025-1. 2025. Available online: <https://www.iucnredlist.org> (accessed on 27 August 2025).
75. Fernandes, G.W.; Santos, R.; Barbosa, N.P.U.; Almeida, H.A.; Carvalho, V.; Angrisano, P. Occurrence of non-native and exotic plants in restored areas of rupestrian grasslands. *Planta Daninha* **2015**, *33*, 463–482. [\[CrossRef\]](#)
76. Murchie, E.H.; Burgess, A.J. Casting light on the architecture of crop yield. *Crop Environ.* **2022**, *1*, 74–85. [\[CrossRef\]](#)
77. Edwards, E.; Osborne, C.; Strömberg, C.; Smith, S. The Origins of C4 Grasslands: Integrating Evolutionary and Ecosystem Science. *Science* **2010**, *328*, 587–591. [\[CrossRef\]](#)
78. Medina, E.; Martinelli, L.A.; Barbosa, E.M.; Victória, R.L. Natural abundance of  $\delta^{13}C$  in tropical grasses from the inpa, instituto nacional de pesquisas da amazônia, herbarium. *Rev. Bras. Bot.* **1999**, *22*, 44–51. [\[CrossRef\]](#)
79. McSteen, P.; Kellogg, E. Molecular, cellular, and developmental foundations of grass diversity. *Science* **2022**, *377*, 599–602. [\[CrossRef\]](#)
80. Pilon, N.A.L.; Cava, M.G.B.; Hoffmann, W.A.; Abreu, R.C.R.; Fidelis, A.; Durigan, G. The diversity of post-fire regeneration strategies in the cerrado ground layer. *J. Ecol.* **2021**, *109*, 154–166. [\[CrossRef\]](#)
81. Zupo, T.; Felipe Daibes, L.; Pausas, J.G.; Fidelis, A. Post-fire regeneration strategies in a frequently burned Cerrado community. *J. Veg. Sci.* **2021**, *32*, e12968. [\[CrossRef\]](#)
82. Fidelis, A.; Zironi, H.L.; Rossatto, D.R.; Zanzarini, V. Fire stimulates grass flowering in the Cerrado independent of season. *J. Veg. Sci.* **2022**, *33*, e13125. [\[CrossRef\]](#)
83. Dairel, M.; Fidelis, A. How does fire affect germination of grasses in the Cerrado? *Seed Sci. Res.* **2020**, *30*, 275–283. [\[CrossRef\]](#)
84. Petersen, K.; Kellogg, E. Diverse ecological functions and the convergent evolution of grass awns. *Am. J. Bot.* **2022**, *109*, 1331–1345. [\[CrossRef\]](#)
85. Bam, S.; Ott, J.; Butler, J.; Xu, L. Belowground mechanism reveals climate change impacts on invasive clonal plant establishment. *Sci. Rep.* **2022**, *12*, 2860. [\[CrossRef\]](#)
86. Yuan, J.; Wang, P.; Yang, Y. Effects of Simulated Herbivory on the Vegetative Reproduction and Compensatory Growth of *Hordeum brevisubulatum* at Different Ontogenic Stages. *Int. J. Environ. Res. Public Health* **2019**, *16*, 1663. [\[CrossRef\]](#) [\[PubMed\]](#)
87. Yuan, J.; Li, H.; Yang, Y. The Compensatory Tillering in the Forage Grass *Hordeum brevisubulatum* After Simulated Grazing of Different Severity. *Front. Plant Sci.* **2020**, *11*, 792. [\[CrossRef\]](#) [\[PubMed\]](#)
88. Benson, E.; Hartnett, D. The Role of Seed and Vegetative Reproduction in Plant Recruitment and Demography in Tallgrass Prairie. *Plant Ecol.* **2006**, *187*, 163–178. [\[CrossRef\]](#)
89. Ma, Z.; Guo, D.; Xu, X.; Lu, M.; Bardgett, R.D.; Eissenstat, D.M.; McCormack, M.L.; Hedin, L.O. Evolutionary history resolves global organization of root functional traits. *Nature* **2018**, *555*, 94–97. [\[CrossRef\]](#) [\[PubMed\]](#)
90. Wargowsky, I.; NeSmith, J.; Holdo, R. Root vascular traits differ systematically between African savanna tree and grass species, with implications for water use. *Am. J. Bot.* **2021**, *108*, 83–90. [\[CrossRef\]](#)
91. Zhang, A.; Li, X.; Zeng, F.; Jiang, Y.; Wang, R. Variation characteristics of different plant functional groups in alpine desert steppe of the Altun Mountains, northern Qinghai-Tibet Plateau. *Front. Plant Sci.* **2022**, *13*, 961692. [\[CrossRef\]](#)
92. Viana, W.; Scharwies, J.; Dinnen, J. Deconstructing the root system of grasses through an exploration of development, anatomy and function. *Plant Cell Environ.* **2022**, *45*, 602–619. [\[CrossRef\]](#)
93. Grace, J.; José, J.S.; Meir, P.; Miranda, H.S.; Montes, R.A. Productivity and carbon fluxes of tropical savannas. *J. Biogeogr.* **2006**, *33*, 387–400. [\[CrossRef\]](#)
94. Tessema, G.B.; Adimassu, D.H.Z.; Wilson, B. Soil Carbon Storage Potential of Tropical Grasses: A Review. *Bot.—Recent Adv. Appl.* **2021**, 97835. [\[CrossRef\]](#)
95. Zhou, Y.; Bomfim, B.; Bond, W.J.; Boutton, T.W.; Case, M.F.; Coetsee, C.; Davies, A.B.; February, E.C.; Gray, E.F.; Silva, L.C.R.; et al. Soil carbon in tropical savannas mostly derived from grasses. *Nat. Geosci.* **2023**, *16*, 710–716. [\[CrossRef\]](#)
96. Andrade, B.O.; Gamboa, C.H.; Ferreira, G.W.D.; Wiesmeier, M.; Assad, E.D.; Cerri, C.E.P.; Mello, J.M.; Morais, V.A.; Overbeck, G.E.; Pinto-Junior, H.V.; et al. The GrassSyn dataset: Soil organic carbon stocks in Brazilian grassy ecosystems. *J. Environ. Qual.* **2025**, *54*, 335–348. [\[CrossRef\]](#) [\[PubMed\]](#) [\[PubMed Central\]](#)
97. Rossatto, D.R.; da Silveira Lobo Sternberg, L.; Franco, A.C. The partitioning of water uptake between growth forms in a Neotropical savanna: Do herbs exploit a third water source niche? *Plant Biol.* **2013**, *15*, 84–92. [\[CrossRef\]](#) [\[PubMed\]](#)
98. Ferreira, M.M.A.A.; Conceição, A.A. Alocação preferencial de recursos e morfologia de órgãos subterrâneos em plantas resistentes ao fogo em vegetação campestre. *Sitientibus* **2012**, *12*, 143–149. [\[CrossRef\]](#)
99. Brum, M., Jr. Partição de Recursos Hídricos em Comunidades Vegetais de Campo Rupestre e Campo de Altitude no Sudeste Brasileiro—Brasil. Master's Dissertation, University of Campinas, São Paulo, Brazil, 2013.
100. Negreiros, D.; Stradic, S.L.; Fernandes, G.W.; Rennó, H.C. Csr analysis of plant functional types in highly diverse tropical grasslands of harsh environments. *Plant Ecol.* **2014**, *215*, 379–388. [\[CrossRef\]](#)

101. Grime, J.P.; Pierce, S. *The Evolutionary Strategies That Shape Ecosystems*; Wiley-Blackwell: Chichester, UK, 2012.
102. Fernandes, G.; Tameirão, L.; Costa, A.; Ribeiro, D.; Neves, M.; Brito, B.; Negreiros, D. Functional traits of three major invasive grasses in a threatened tropical mountain grassland. *An. Acad. Bras. Ciênc.* **2021**, *93*, e20200119. [\[CrossRef\]](#)
103. Frost, M.D.T.; Trimas, G.E.; Johnston, K.A.; Bunch, Z.L.T.; Jolin, A.D.; Koerner, S.E. Native plant species exhibit consistent drought advantage over introduced species until additional global change drivers are included: A grassland meta-analysis. *J. Ecol.* **2025**, *113*, 2698–2711. [\[CrossRef\]](#)
104. Baeta, H.E. Contribuição da deposição úmida (chuva e neblina) nas relações hídricas e nutricionais de fisionomias de campos ferruginosos na serra da Brígida, Ouro Preto, MG. Master's Thesis, Universidade Federal de Ouro Preto, Minas Gerais, Brazil, 2012. Available online: <http://www.repositorio.ufop.br/handle/123456789/12806> (accessed on 20 October 2025).
105. Boanares, D.; Isaias, R.R.M.S.; Sousa, H.C.d.; Kozovits, A.R. Strategies of leaf water uptake based on anatomical traits. *Plant Biol.* **2018**, *20*, 848–856. [\[CrossRef\]](#)
106. Boanares, D.; Lemos-Filho, J.P.; Isaias, R.M.S.; França, M.G.C. Photosynthetic heat tolerance in plants with different foliar water-uptake strategies. *Am. J. Bot.* **2021**, *108*, 811–819. [\[CrossRef\]](#) [\[PubMed\]](#)
107. Li, C.; Mo, Y.; Wang, N.; Xing, L.; Yang, Q.; Chen, Y.; Yuan, Z.; Ali, A.; Qi, J.; Fernández, V.; et al. The overlooked functions of trichomes: Water absorption and metal detoxication. *Plant Cell Environ.* **2023**, *46*, 669–687. [\[CrossRef\]](#)
108. Filgueiras, T.S. *Gramíneas do Cerrado—Póstuma Edition*; IBGE: Rio de Janeiro, Brazil, 2021; 630p, ISBN 978-65-87201-68-9. Available online: <https://biblioteca.ibge.gov.br/visualizacao/livros/liv101834.pdf> (accessed on 19 October 2025).
109. Nobel, P.S.; Schulte, P.J.; North, G.B. Water influx characteristics and hydraulic conductivity for roots of *Agave deserti* Engelm. *J. Exp. Bot.* **1990**, *41*, 409–415. [\[CrossRef\]](#)
110. Andrade, E.S.; Souza, B.C.O.Q.; Costa, E.; Bonezio, H.; Assefa, M.K.; Pires-Lira, M.F.; Morais, L.E.; Marchiori, P.E.R.; Nascimento, V.L. Distinct morphophysiological responses of the native c4 grasses *Axonopus siccus* and *Eragrostis polytricha* to shading. *Flora* **2024**, *320*, 152621. [\[CrossRef\]](#)
111. Abrahão, A.; de Britto Costa, P.; Lambers, H.; Andrade, S.A.L.; Sawaya, A.C.H.F.; Ryan, M.H.; Oliveira, R.S. Soil types select for plants with matching nutrient-acquisition and-use traits in hyperdiverse and severely nutrient-impovertised *campos rupestres* and cerrado in central Brazil. *J. Ecol.* **2018**, *107*, 1302–1316. [\[CrossRef\]](#)
112. Camargo, A.P.; de Souza, R.S.C.; Jose, J.; Gerhardt, I.R.; Dante, R.A.; Mukherjee, S.; Huntemann, M.; Kyrpides, N.C.; Carazzolle, M.F.; Arruda, P. Plant microbiomes harbor potential to promote nutrient turnover in impoverished substrates of a Brazilian biodiversity hotspot. *ISME J.* **2022**, *17*, 354–370. [\[CrossRef\]](#)
113. de Paula, A.F.; Cruz, F.P.N.; Dinato, N.B.; de Andrade, P.H.M.; de Moraes, A.C.P.; Junior, W.B.; Bernardi, A.C.C.; Vigna, B.B.Z.; Fávero, A.P.; Lacava, P.T. Endophytic and rhizospheric bacteria associated with *Paspalum atratum* and its potential for plant growth promotion with different phosphate sources. *Front. Plant Sci.* **2022**, *13*, 884716. [\[CrossRef\]](#)
114. Trevisani, N.V.; Cirilo, A.C.; da Silva, D.V.; Figueiredo, M.A.; Messias, M.C.T.B.; Kozovits, A.R. Anais do XV LASEAC (Latin American Symposium on Environmental Analytical Chemistry) & X ENQAmb. In Proceedings of the XV Latin American Symposium on Environmental Analytical Chemistry & X National Meeting of Environmental Chemistry, Ouro Preto, Brazil, 18–21 March 2024; ISBN 978-65-272-0404-6. [\[CrossRef\]](#)
115. Singh, J.S.; Pandey, V.C.; Singh, D.P. Efficient soil microorganisms: A new dimension for sustainable agriculture and environmental development. *Agric. Ecosyst. Environ.* **2011**, *140*, 339–353. [\[CrossRef\]](#)
116. Figueiredo, M.A.; Messias, M.C.T.B.; Leite, M.G.P.; Kozovits, A.R. Direct seeding in the restoration of post-mined campo rupestre: Germination and establishment of 14 native species. *Flora* **2021**, *276*, 151772. [\[CrossRef\]](#)
117. Figueiredo, M.A.; Diniz, A.P.; Abreu ATd Messias, M.C.T.B.; Kozovits, A.R. Growing *Periandra mediterranea* on post-mining substrate: Native Fabaceae with potential for revegetation of degraded rupestrian grasslands in Brazil. *Acta Bot. Bras.* **2018**, *32*, 232–239. [\[CrossRef\]](#)
118. Figueiredo, M.A.; da Silva, T.H.; Pinto, O.H.B.; Leite, M.G.P.; de Oliveira, F.S.; Messias, M.C.T.B.; Rosa, L.H.; Câmara, P.E.A.S.; Lopes, F.A.C.; Kozovits, A.R. Metabarcoding of Soil Fungal Communities in Rupestrian Grassland Areas Preserved and Degraded by Mining: Implications for Restoration. *Microb. Ecol.* **2023**, *85*, 1045–1055. [\[CrossRef\]](#)
119. Marques, T.E.D.; Baêta, H.E.; Leite, M.G.P.; Martins, S.V.; Kozovits, A.R. Growth of cerrado native species and of *Vetiveria zizanioides* in colluvium of Gullies. *Ciênc. Florest.* **2014**, *24*, 843–856. [\[CrossRef\]](#)
120. Veldman, J.W.; Overbeck, G.E.; Negreiros, D.; Mahy, G.; Le Stradic, S.; Fernandes, G.W.; Durigan, G.; Buisson, E.; Putz, F.E.; Bond, W.J. Where tree planting and forest expansion are bad for biodiversity and ecosystem services. *BioScience* **2015**, *65*, 1011–1018. [\[CrossRef\]](#)
121. Buisson, E.; Fidelis, A.; Overbeck, G.E.; Schmidt, I.B.; Durigan, G.; Young, T.P.; Alvarado, T.; Arruda, A.J.; Boisson, S.; Bond, W.; et al. A research agenda for the restoration of tropical and subtropical grasslands and savannas. *Restor. Ecol.* **2021**, *29*, e13292. [\[CrossRef\]](#)
122. Silva, M.C.; Moonlight, P.; Oliveira, R.S.; Pennington, R.T.; Rowland, L. Toward diverse seed sourcing to upscale ecological restoration in the Brazilian Cerrado. *Front. Ecol. Evolutio* **2022**, *10*, 1045591. [\[CrossRef\]](#)

123. Silveira, F.A.O.; Arruda, A.J.; Bond, W.; Durigan, G.; Fidelis, A.; Kirkman, K.; Oliveira, R.S.; Overbeck, G.E.; Sansevero, J.B.B.; Siebert, F.; et al. Myth-busting tropical grassy biome restoration. *Restor. Ecol.* **2020**, *28*, 1067–1073. [CrossRef]
124. Silveira, F.A.O.; Ordóñez-Parra, C.A.; Moura, L.C.; Schmidt, I.B.; Andersen, A.N.; Bond, W.; Buisson, E.; Durigan, G.; Fidelis, A.; Oliveira, R.S.; et al. Biome Awareness Disparity is BAD for tropical ecosystem conservation and restoration. *J. Appl. Ecol.* **2022**, *59*, 1967–1975. [CrossRef]
125. Bessa, L.F.F. Qualidade de Sementes, Crescimento e Biomassa de Gramíneas Nativas do Cerrado. Dissertação de Mestrado, Mestrado em Ciências Florestais, Universidade de Brasília, Brasília, Brazil, 2024. Available online: <http://repositorio2.unb.br/handle/10482/51877> (accessed on 18 October 2025).
126. Ramos, D.M.; Liaffa, A.B.S.; Diniz, P.; Munhoz, C.B.R.; Ooi, M.K.J.; Borghetti, F.; Valls, J.F.M. Seed tolerance to heating is better predicted by seed dormancy than by habitat type in Neotropical savanna grasses. *Int. J. Wildland Fire* **2016**, *25*, 1273–1280. [CrossRef]
127. Ramos, D.M.; Valls, J.F.M.; Borghetti, F.; Ooi, M. Fire cues trigger germination and stimulate seedling growth of grass species from Brazilian savannas. *Am. J. Bot.* **2019**, *106*, 1190–1201. [CrossRef]
128. Carmona, R.; Martins, C.R.; Fávero, A.P. Fatores que afetam a germinação de sementes de gramíneas nativas do Cerrado. *Rev. Bras. Sementes* **1998**, *20*, 16–22.
129. Carmona, R.; Camilo, M.G.B.; Martins, C.R. Estimulo à germinação em sementes de *Gymnopogon doellii* uma gramínea ameaçada de extinção. *Rev. Bras. Fisiol. Veg.* **1997**, *9*, 125–130.
130. Aires, S.S.; Sato, M.N.; Miranda, H.S. Seed characterization and direct sowing of native grass species as a management tool. *Grass Forage Sci.* **2014**, *69*, 470–478. [CrossRef]
131. Paredes, M.V.F.; Cunha ALNd Musso, C.; Aires, S.S.; Sato, M.N.; Miranda, H.S. Germination responses of native and invasive cerrado grasses to simulated fire temperatures. *Plant Ecol. Divers.* **2018**, *11*, 193–203. [CrossRef]
132. Figueiredo, M.; Diniz, A.; Messias, M.; Kozovits, A. Propagation and establishment of rupestrian grassland grasses for restoration of degraded areas by mining. *Braz. J. Bot.* **2018**, *41*, 287–295. [CrossRef] [PubMed]
133. Souza, C.S.; Ramos, D.M.; Barbosa, E.R.M.; Borghetti, F. Germination of grass species from dry and wet grasslands in response to osmotic stress under present and future temperatures. *Am. J. Bot.* **2022**, *109*, 2018–2029. [CrossRef] [PubMed]
134. Giotto, A.C. Avaliação do Desenvolvimento dos Componentes Arbóreos e Herbáceos na Recuperação de Áreas Degradadas na Bacia do Ribeirão do Gama, Distrito Federal. Dissertação de Mestrado, Mestrado em Ciências Florestais, Universidade de Brasília, Brasília, Brazil, 2010. Available online: <http://repositorio2.unb.br/handle/10482/7550> (accessed on 20 October 2025).
135. Cirilo, A.C. Germinação de gramíneas (Poaceae) nativas de campos rupestres e efeito de microorganismos eficientes. Monografia. Graduação em Ciências Biológicas Bacharelado, Universidade Federal de Ouro Preto, Ouro Preto, Brazil, 2025. Available online: <https://www.monografias.ufop.br/handle/35400000/7505> (accessed on 20 October 2025).
136. Zanetti, M.; Dayrell, R.L.C.; Wardil, M.V.; Damasceno, A.; Fernandes, T.; Castilho, A.; Santos, F.M.G.; Silveira, F.A.O. Seed Functional Traits Provide Support for Ecological Restoration and Ex Situ Conservation in the Threatened Amazon Iron stone Outcrop Flora. *Front. Plant Sci.* **2020**, *11*, 599496. [CrossRef] [PubMed]
137. Musso, C.; Miranda, H.S.; Aires, S.S.; Bastos, C.; Soares, A.M.V.M.; Loureiro, S. Simulated post-fire temperature affects germination of native and invasive grasses in cerrado (Brazilian savanna). *Plant Ecol. Divers.* **2015**, *8*, 219–227. [CrossRef]
138. Figueiredo, M.A.; Baêta, H.E.; Kozovits, A.R. Germination of native grasses from the Quadrilátero Ferrífero with potential application in the recovery of degraded areas. *Biota Neotrop.* **2012**, *12*, 118–123. [CrossRef]
139. Fontenele, H.G.V.; Cruz-Lima, L.F.S.; Pacheco-Filho, J.L.; Miranda, H.S. Burning grasses, poor seeds: Post-fire reproduction of early-flowering Neotropical savanna grasses produces low-quality seeds. *Plant Ecol.* **2020**, *221*, 1265–1274. [CrossRef]
140. Motta, G.S.T.; Pilon, N.; Fidelis, A.; Kolb, R.M. Smoke effects on the germination of Cerrado species. *Plant Ecol.* **2024**, *225*, 685–693. [CrossRef]
141. de Oliveira, A.C.C. Produção e Plantio de mudas de Gramíneas Nativas para Restauração de Fisionomias Abertas do Cerrado. Ph.D. Thesis, Doutorado em Recursos Florestais, Universidade de São Paulo, Piracicaba, Brazil, 2023. [CrossRef]
142. Figueiredo, M.A.; Messias, M.C.T.B.; Leite, M.G.P.; Kozovits, A.R. Seed covering and dry periods in the rainy season interfere with direct seeding success in the restoration of post-mined grasslands. *Ecol. Austral* **2021**, *31*, 444–455. [CrossRef]
143. Pellizzaro, K.F.; Cordeiro, A.O.O.; Alves, M.; Motta, C.P.; Rezende, G.M.; Silva, R.R.P.; Ribeiro, J.F.; Sampaio, A.B.; Vieira, D.L.M.; Schmidt, I.B. Cerrado restoration by direct seeding: Field establishment and initial growth of 75 trees, shrubs and grass species. *Braz. J. Bot.* **2017**, *40*, 681–693. [CrossRef]
144. Pedrini, S.; Gibson-Roy, P.; Trivedi, C.; Gálvez-Ramírez, C.; Hardwick, K.; Shaw, N.; Frischie, S.; Laverack, G.; Dixon, K. Collection and production of native seeds for ecological restoration. *Restor. Ecol.* **2020**, *28*, S228–S238. [CrossRef]
145. Pedrini, S.; Balestrazzi, A.; Madsen, M.; Bhalsing, K.; Hardegree, S.; Dixon, K.; Kildisheva, O. Seed enhancement: Getting seeds restoration-ready. *Restor. Ecol.* **2020**, *28*, S266–S275. [CrossRef]
146. de Oliveira, A.C.C.; Forti, V.A.; Viani, R.A.G. Fertility responses of a native grass: Technology supporting native plant production for restoration in Brazil. *Restor. Ecol.* **2022**, *30*, e13534. [CrossRef]

147. de Oliveira, A.C.C.; Forti, V.A.; de Paula Loiola, P.; Viani, R.A.G. Techniques for seedling production of two native grasses: New perspectives for Brazilian Cerrado restoration. *Restor. Ecol.* **2020**, *28*, 297–303. [\[CrossRef\]](#)
148. Matheus, L.I.; Oliveira, A.C.C.d.e.; Viani, R.A.G. Vegetative multiplication of native Cerrado grasses for ecological restoration. *Restor. Ecol.* **2025**, *33*, e70050. [\[CrossRef\]](#)
149. Sena, L.; Bahia, T.O.; Fernandes, G.W. Vegetative propagation of *Schizachyrium tenerum* (Poaceae) under different substrates and environments. *Floresta Ambiente* **2021**, *28*, e20200051. [\[CrossRef\]](#)
150. Paulo, M.L. Prospecção e Conservação de *Gymnopogon doellii* (poaceae), Espécie Criticamente Ameaçada. Tese de Doutorado, Doutorado em Botânica, Universidade de Brasília, Brasília, Brazil, 2024. Available online: [https://repositorio.unb.br/bitstream/10482/51777/1/MaikyLopesPaulo\\_TESE.pdf](https://repositorio.unb.br/bitstream/10482/51777/1/MaikyLopesPaulo_TESE.pdf) (accessed on 20 October 2025).
151. Arruda, A.; Medeiros, N.; Fiorini, C.; Ordóñez-Parra, C.; Dayrell, R.; Messeder, J.; Zanetti, M.; Wardil, M.; Paiva, D.; Kozovits, A.R.; et al. Ten principles for restoring campo rupestre, a threatened tropical, megadiverse, nutrient-impovertised montane grassland. *Restor. Ecol.* **2023**, *31*, e1392431. [\[CrossRef\]](#)
152. Coutinho, A.G.; Alves, M.; Sampaio, A.B.; Schmidt, I.B.; Vieira, D.L.M. Effects of initial functional-group composition on assembly trajectory in savanna restoration. *Appl. Veg. Sci.* **2019**, *22*, 61–70. [\[CrossRef\]](#)
153. Sampaio, A.B.; Vieira, D.L.M.; Holl, K.D.; Pellizzaro, K.F.; Alves, M.; Coutinho, A.G.; Cordeiro, A.; Ribeiro, J.F.; Schmidt, I.B. Lessons on direct seeding to restore Neotropical savanna. *Ecol. Eng.* **2019**, *138*, 148–154. [\[CrossRef\]](#)
154. Le Stradic, S.; Silveira, F.A.O.; Buisson, E.; Cazelles, K.; Carvalho, V.; Fernandes, G.W. Diversity of germination strategies and seed dormancy in herbaceous species of campo rupestre grasslands. *Austral Ecol.* **2015**, *2*, 537–546. [\[CrossRef\]](#)
155. Le Stradic, S.; Fernandes, G.; Buisson, É. No recovery of campo rupestre grasslands after gravel extraction: Implications for conservation and restoration. *Restor. Ecol.* **2018**, *26*, S151–S159. [\[CrossRef\]](#)
156. Silva, R.R.; Coelho, F.T.A.; dos Anjos, M.A.; Vaz Filho, V. Controle do Capim-gordura nas Áreas de Recuperação Ambiental da Mineração Corumbaense Reunida (MCR), Corumbá, MS. *Biodiversidade Bras.* **2013**, *3*, 237–242. [\[CrossRef\]](#)
157. Lima, C.T.; Furtini Neto, A.E.; Giulietti, A.M.; Mota, N.F.O.; Braga, R.P.; Viana, P.L. *Guia de Plantas para a Recuperação de Áreas Degradadas nas Cangas do Quadrilátero Ferrífero de Minas Gerais*; Fundação Brasil Cidadão: Fortaleza, Brasil, 2016; 179p.
158. Mazzochini, G.G.; Martins, D.L.; Barros, F.V.; Oliveira, A.C.C.; Xavier, R.O.; Furtado, M.N.; Verona, L.S.; Viani, R.A.G.; Rowland, L.; Oliveira, R.S. Effects of grass functional diversity on invasion success by exotic grasses in Cerrado grasslands. *J. Appl. Ecol.* **2024**, *61*, 271–280. [\[CrossRef\]](#)
159. de Castro, A.F.; Boaneres, D.; de Medeiros Sarmiento, P.S.; Caldeira, C.F.; Michelan, T.S.; Ramos, S.J.; Gastauer, M. Fertilization during mineland rehabilitation may shift competitive outcomes toward invasive species. *Restor. Ecol.* **2024**, *32*, e14108. [\[CrossRef\]](#)
160. Figueiredo, M.A. (Universidade Federal de Ouro Preto, Ouro Preto, Minas Gerais, Brazil). Personal communication, 2025.
161. BRASIL. Lei nº 14.066, de 30 de Setembro de 2020. Altera a Lei nº 12.334, de 20 de Setembro de 2010, que Estabelece a Política Nacional de Segurança de Barragens. Diário Oficial da União: Seção 1, Brasília, DF, 1º out. 2020. Available online: <https://pesquisa.in.gov.br/imprensa/jsp/visualiza/index.jsp?data=01/10/2020&jornal=515&pagina=3&totalArquivos=886> (accessed on 19 October 2025).
162. Mendonça, M.P.; Santos, F.M.G.; Arruda, L.J. Resgate de espécies vegetais dos campos ferruginosos em área de mineração—Mina de Minério de Ferro Capão Xavier, Nova Lima, MG. In *Recuperando o Verde para as Cidades: A Experiência dos Jardins Botânicos Brasileiros*; Sampaio, T., Costa, M.L.M.N., Jackson, P.W., Eds.; RBJB/IPJBRJ/BGCI: Rio de Janeiro, Brazil, 2007; pp. 87–98.
163. Carvalho, A.C.; Pereira, I.M.; de Lima, A.O.; Zanuncio, J.C.; Rech, A.R.; Siqueira, W.K.; Fernandes, G.W. Reintroduction of native species in an ecological restoration program from a quartzite area of campos rupestres. *Plant Soil* **2025**, *511*, 1033–1048. [\[CrossRef\]](#)
164. de Paula, K.A. Resgate de Gramínea Nativa: Alternativa para a Restauração Ecológica de Campo Rupestre. Dissertação de Mestrado, Mestrado em Ciência Florestal, Universidade Federal dos Vales do Jequitinhonha e Mucuri, Diamantina, Brazil, 2020. Available online: <https://repositorio.ufvjm.edu.br/items/c7dba975-70e5-4696-89c9-d0344ee16e03> (accessed on 18 October 2025).
165. Hancock, N.; Hughes, L. Turning up the heat on the provenance debate: Testing the ‘local is best’ paradigm under heatwave conditions. *Austral Ecol.* **2014**, *39*, 600–611. [\[CrossRef\]](#)
166. Garcia, Q.S.; Barreto, L.C.; Bicalho, E.M. Environmental factors driving seed dormancy and germination in tropical ecosystems: A perspective from campo rupestre species. *Environ. Exp. Bot.* **2020**, *178*, 104164. [\[CrossRef\]](#)
167. Faria, F.; Ordóñez-Parra, C.; Granata, L.; Resende, L.; Silveira, F. Low-cost technology supports propagation of endemic species from a global biodiversity hotspot. *Restor. Ecol.* **2025**, *33*, e70005. [\[CrossRef\]](#)
168. do Carmo, F.F.; de Campos, I.C.; Jacobi, C.M. Effects of fine-scale surface heterogeneity on rock outcrop plant community structure. *J. Veg. Sci.* **2016**, *27*, 50–59. [\[CrossRef\]](#)
169. Gastauer, M.; Ramos, S.J.; Caldeira Júnior, C.F.; Siqueira, J.O. Reintroduction of native plants indicates the return of ecosystem services after iron mining at the Urucum Massif. *Ecosphere* **2021**, *12*, e03762. [\[CrossRef\]](#)
170. Schmidt, I.; De Urzedo, D.; Piña-Rodrigues, F.; Vieira, D.; De Rezende, G.; Sampaio, A.; Junqueira, R. Community-based native seed production for restoration in Brazil—The role of science and policy. *Plant Biol.* **2018**, *21*, 389–397. [\[CrossRef\]](#)

171. Padovezi, A.; Adams, C.; Chazdon, R.; Mendonça, M.; Secco, L.; Campos-Filho, E.; Sampaio, A.; Damasceno, E.; Albuquerque, N.; Santarem, F.; et al. Native seed collector networks in Brazil: Sowing social innovations for transformative change. *People Nat.* **2024**, *6*, 1905–1921. [CrossRef]
172. Raupp, P.P.; Ferreira, M.C.; Alves, M.; Campos-Filho, E.M.; Sartorelli, P.A.R.; Consolaro, H.N.; Vieira, D.L.M. Direct seeding reduces the costs of tree planting for forest and savanna restoration. *Ecol. Eng.* **2020**, *148*, 105788. [CrossRef]
173. Bahia, T.; Almeida, H.; Barbosa, M.; Negreiros, D.; Quesada, M.; Fernandes, G.W. Positive response of seedlings from an old-growth grassland to soil quality improvement. *Braz. J. Bot.* **2020**, *43*, 1037–1045. [CrossRef]
174. Colado, M.; Reis, L.; Guerra, A.; Guerin, N.; Szabo, J.; Garcia, L. Mixing Green Manure with Native Seeds in the Same Row Enhances Species Establishment in Restoration Areas of the Brazilian Cerrado. *Appl. Veg. Sci.* **2025**, *28*, e70015. [CrossRef]
175. Menezes, L.S.; Vogel Ely, C.; Lucas, D.B.; Minervini, G.H.; Boldrini, I.I.; Overbeck, G.E. Plant species richness record in Brazilian Pampa grasslands and implications. *Braz. J. Bot.* **2018**, *41*, 817–823. [CrossRef]
176. Rolim, R.; Rosenfield, M.; Overbeck, G. Are we ready to restore South Brazilian grasslands? Plant material and legal requirements for restoration and plant production. *Acta Bot. Bras.* **2022**, *36*, e2021abb0155. [CrossRef]
177. Mapbiomas 2024. Destaques do Mapeamento Anual de Cobertura e Uso da Terra. Available online: [https://brasil.mapbiomas.org/wp-content/uploads/sites/4/2024/09/Factsheet-Cerrado\\_C9\\_17.09.24\\_FG-e-AG\\_v3.pdf](https://brasil.mapbiomas.org/wp-content/uploads/sites/4/2024/09/Factsheet-Cerrado_C9_17.09.24_FG-e-AG_v3.pdf) (accessed on 20 October 2025).
178. Instituto Brasileiro de Mineração (IBRAM). Desempenho da Mineração em 2024. Available online: [https://ibram.org.br/noticia/desempenho\\_da\\_mineracao\\_2024/](https://ibram.org.br/noticia/desempenho_da_mineracao_2024/) (accessed on 2 September 2025).
179. Custom Market Insights Global Native Grass Seeds Market 2024–2033. 2024. Available online: <https://www.custommarketinsights.com/report/native-grass-seeds-market/#report-description> (accessed on 19 October 2025).
180. Freire, J.M.; Urzedo, D.I.; Piña-Rodrigues, F.C.M. A realidade das sementes nativas no Brasil: Desafios e oportunidades para a produção em larga escala. *Seed News* **2017**, *21*, 24–28.
181. Urzedo, D.; Piña-Rodrigues, F.; Feltran-Barbieri, R.; Junqueira, R.; Fisher, R. Seed Networks for Upscaling Forest Landscape Restoration: Is It Possible to Expand Native Plant Sources in Brazil? *Forests* **2020**, *11*, 259. [CrossRef]
182. De Urzedo, D.; Fisher, R.; Piña-Rodrigues, F.; Freire, J.; Junqueira, R. How policies constrain native seed supply for restoration in Brazil. *Restor. Ecol.* **2019**, *27*, 768–774. [CrossRef]
183. Dutra-Silva, R.; Overbeck, G.; Müller, S. How can Brazilian legislation on native seeds advance based on good practices of restoration in other countries? *Perspect. Ecol. Conserv.* **2024**, *22*, 224–231. [CrossRef]
184. Nevill, P.G.; Cross, A.T.; Dixon, K.W. Ethical seed sourcing is a key issue in meeting global restoration targets. *Curr. Biol.* **2018**, *28*, R1378–R1379. [CrossRef] [PubMed]
185. Nelson, C.R.; Hallett, J.G.; Romero Montoya, A.E.; Andrade, A.; Besacier, C.; Boerger, V.; Bouazza, K.; Chazdon, R.; Cohen-Shacham, E.; Danano, D.; et al. *Standards of Practice to Guide Ecosystem Restoration—A Contribution to the United Nations Decade on Ecosystem Restoration 2021–2030*; FAO: Rome, Italy; Washington, DC, USA; SER/IUCN CEM: Gland, Switzerland, 2024. [CrossRef]
186. Nevill, P.G.; Tomlinson, S.; Elliott, C.P.; Espeland, E.K.; Dixon, K.W.; Merritt, D.J. Seed production areas for the global restoration challenge. *Ecol. Evol.* **2016**, *6*, 7490–7497. [CrossRef] [PubMed]
187. Urzedo, D.; Pedrini, S.; Vieira, D.L.M.; Sampaio, A.B.; Souza, B.D.F.; Campos-Filho, E.M.; Piña-Rodrigues, F.C.M.; Schmidt, I.B.; Junqueira, R.G.P.; Dixon, K. Indigenous and local communities can boost seed supply in the UN decade on ecosystem restoration. *Ambio* **2022**, *51*, 557–568. [CrossRef] [PubMed]
188. Lima, Y.B.C.; Durigan, G.; Souza, F.M. Germination of 15 Cerrado plant species under different light conditions. *Biosci. J.* **2014**, *30*, 1864–1872. Available online: <https://seer.ufu.br/index.php/biosciencejournal/article/view/23274> (accessed on 19 October 2025).
189. Kolb, R.M.; Pilon, N.A.L.; Durigan, G. Factors influencing seed germination in cerrado grasses. *Acta Bot. Bras.* **2016**, *30*, 87–92. [CrossRef]
190. Pereira, C.M.; Figueirôa, R.N.A.; Fontenele, H.G.V.; Miranda, H.S. Light affects the germination and normal seedling development of Neotropical savanna grasses. *Seed Sci. Res.* **2021**, *31*, 47–50. [CrossRef]
191. Barbosa, E.G.; Daibes, L.F.; Novais, R.B.; Pivello, V.R.; Fidelis, A. Fire cues and germination of invasive and native grasses in the Cerrado. *Acta Bot. Bras.* **2020**, *34*, 185–191. [CrossRef]
192. Fernandes, A.F.; Oki, Y.; Fernandes, G.W.; Moreira, B. The effect of fire on seed germination of campo rupestre species in the South American Cerrado. *Plant Ecol.* **2021**, *222*, 45–55. [CrossRef]
193. Klink, C.A. Germination and seedling establishment of two native and one invading African grass species in the Brazilian Cerrado. *J. Trop. Ecol.* **1996**, *12*, 139–147. [CrossRef]
194. Fontenele, H.G.V.; Miranda, H.S. Seed ecology of post-fire flowering species from the Cerrado. *Seed Sci. Res.* **2022**, *32*, 222–229. [CrossRef]

195. Saraiva, D.F.; de Paula, C.C.; de Moraes, P.J.; Silva, R.V.; Silva, M.M.; Dias, D.C.F.S.; Botelho, S.A. Seed germination and dormancy break in *Eragrostis polytricha*, a native Brazilian grass species with potential for recovery of degraded lands. *Acta Bot. Bras.* **2020**, *34*, 497–504. [[CrossRef](#)]
196. Martins, C.R.; Borghetti, F.; de Carvalho Moretzsohn, M.; de Noronha, S.E.; Valls, J.F.M. Strategies for reintroduction and conservation of *Gymnopogon doellii*, an endemic grass at risk of extinction. *Rodriguésia* **2022**, *73*, e00942021. [[CrossRef](#)]

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.