Ten principles for restoring campo rupestre , a threatened tropical, megadiverse, nutrient-impoverished montane grassland

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Ten principles for restoring *campo rupestre*, a threatened tropical, megadiverse, nutrient-impoverished montane grassland

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To achieve the ambitious goals of the UN Decade on Ecosystem Restoration, restoration frameworks should embrace the diversity of ecosystems found on Earth, including open-canopy ecosystems, which have been largely overlooked. Considering the paucity of scientific foundations promoting restoration science, policy, and practice for open tropical ecosystems, we provide overarching guidelines to restore the *campo rupestre*, a Neotropical, open megadiverse grassland that has been increasingly threatened by multiple human activities, especially mining. Restoration techniques for tropical grasslands are still at its infancy, and attempts to restore *campo rupestre* have had, so far, low to moderate success, highlighting the need for a tailored restoration framework. In a scenario of increasing degradation and scarcity of on-site restoration experiments, we propose 10 principles to improve our ability to plan, implement, and monitor restoration in *campo rupestre*: (1) include socioeconomic dimensions, (2) implement active restoration, (3) keep low soil fertility, (4) restore disturbance regimes, (5) address genetic structure and adaptation potential, (6) restore geographically restricted and specialized ecological interactions, (7) incorporate functional approaches, (8) use seed-based restoration strategies to enhance biodiversity, (9) translocation is inevitable, and (10) long-term monitoring is mandatory. Our principles represent the best available evidence to support better science and practice for the restoration of *campo rupestre* and, to some extent, can be useful for other megadiverse, fire-prone, and nutrient-poor ecosystems.

Key words: grasslands, mining, OCBIL, tropical grassy biomes, tropical mountains

Author contributions: AJA, FAOS conceived the research; all authors actively discussed ideas, contributed with writing topics, and revised and approved the final version of the manuscript.

Conceptual Implications

- A set of guiding principles for restoration planning, implementing, and monitoring is provided for tropical, open-canopy, nutrient-impoverished ecosystems.
- Our principles have a large potential to improve science, policy, practice, and governance in restoration of *campo rupestre* and analogous ecosystems.
- Testing, expanding, and improving our principles will inevitably result in better restoration outcomes and cobenefits to both people and nature.

Introduction

The UN Decade on Ecosystem Restoration is catalyzing unprecedented efforts to restore ecosystems with the ultimate goals of mitigating climate change, preventing biodiversity erosion, and improving human well-being. To achieve such goals, restoration frameworks should embrace the diversity of ecosystems found on Earth, including open ecosystems such as tropical savannas and grasslands (Dudley et al. 2020), which have been largely overlooked, despite being vital for biodiversity conservation, ecosystem provision, and sustaining human livelihoods (Bond 2019; Buisson et al. 2021, 2022). Unfortunately, restoration techniques for tropical grasslands are still at an initial stage, and no broad restoration framework exists in contrast to those in temperate grasslands or tropical rainforests, where

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concepts, principles, and techniques are well-developed and have been largely tested in the field (Silveira et al. 2020). Application of tropical rainforest- and temperate grassland-centered strategies for tropical grassland restoration results in unsuccessful outcomes and ill-conceived policies and practices (Veldman et al. 2015; Fleischman et al. 2020; Buisson et al. 2021).

Considering the paucity of scientific foundations promoting restoration science, policy, practice, and governance for tropical grasslands, we provide 10 principles to restore the *campo rupestre*, a megadiverse open ecosystem threatened by multiple human activities but particularly affected by quarrying and mining (Fernandes et al. 2018; Fernandes et al. 2023). Full restoration of mined sites is unlikely, but claims supporting repurposing (i.e. the process of making severely degraded land fit for cultivation or a state suitable for some human use; or reuse of infrastructure at another site or derivative business opportunities to create positive economic activity) as the best strategy for post-mining sites are not supported by evidence (Young et al. 2022). The recent release of the International Principles and Standards for the Ecological Restoration and Recovery of Mine Sites is expected to inspire and drive higher and better outcomes in post-mining landscapes (Young et al. 2022). Assessing, planning, implementing, managing, and monitoring post-mining restoration is extremely challenging, but provides an opportunity for stakeholders (e.g. local communities, industry, governments, and NGOs) to support ecosystem recovery processes, enhance biodiversity, and generate socioeconomic benefits, if activities are successfully conducted. Nevertheless, our current understanding of the restoration ecology of *campo rupestre* prevents the broad application of such principles to this particular ecosystem. Our focus here is on *campo rupestre*, but our principles are rooted in restoring analogous ecosystems (Mucina 2018) and, thus, could be useful for other megadiverse, fire-prone, and nutrient-poor ecosystems like the South African *fynbos*, the Australian *kwongan*, South American *tepuis*, the New Caledonia *maquis*, heathlands in Central Madagascar, or ferricretes in the Western Ghats (Hopper et al. 2021).

Our guiding principles draw from emerging knowledge on *campo rupestre* and evidence-based restoration initiatives developed in similar ecosystems elsewhere characterized by high habitat heterogeneity, geographically structured endemism, fire, and extremely impoverished soils (Holmes & Richardson 1999; Elliott et al. 2022; Barros-Souza & Borges 2023). We briefly introduce the ecology, threats, and challenges to restoring *campo rupestre*. Then, we explain the concepts underpinning our restoration guidelines and propose 10 principles to improve our ability to tailor restoration strate- gies that can be, to some extent, applicable to similar open nutrient-impoverished ecosystems.

The Ecology, Threats, and Challenges to Campo Rupestre Restoration

Campo rupestre is an ancient, megadiverse, fire-prone grassland, associated with nutrient-impoverished quartzites and ferruginous rocks in South American mountains, but is particularly prevalent at the Espinhaço Range, Eastern Brazil. *Campo rupestre* covers an area of <0.8% of Brazil, but hosts more than 15% of the national flora, with >40% endemics (Miola et al. 2021). The climatic regime in *campo rupestre* consists of markedly dry winters and wet summers, with total precipitation ranging from 1,630 mm/year (in the south) to 900 mm/year (in the north). Astriking feature of the *campo rupestre* landscape is the diversityof soil environments and vegetation mosaics, largely determined by local topography and microenvironmental aspects. When developed on quartzite and sandstone, the soils are typically acidic, shallow white sands over parent rock, have a low water-holding capacity, and are extremely impoverished, particularly in plant-available phosphorus (P) (Mucina 2018). Soils developed on ironstones are also shallow and acidic, with a low water-holding capacity, but exhibit lower concentrations of exchangeable aluminum (Al) and higher iron (Fe) and manganese (Mn) concentrations (Oliveira et al. 2016). *Campo rupestre* provides key ecosystem services—such as belowground carbon storage, water provision, pollination, and ecotourism—that extend far beyond its area, reaching some of the most populated Brazilian urban centers (Fernandes et al. 2020). Major threats to its megadiversity include opencast mining, urban expansion, overharvesting, uncontrolled tourism, and climate change (Fig. 1) (Miola et al. 2021).

Selection by extremely impoverished soils in *campo rupestre* have resulted in the evolution of a suite of traits that pose both unusual and additional challenges for ecological restoration (Hopper et al. 2021), including (1) philomatry (or reduced seed dispersibility; Cheplick 2022), which limits dispersal into degraded areas (Arruda et al. 2021; Bastos et al. 2022), (2) slow growth rates (Dayrell et al. 2018), (3) resource allocation to resprouting from underground storage organs (USOs) and vegetative propagation rather than annual/regular sexual reproduction after disturbances (e.g. fire, herbivory; Le Stradic et al. 2018); and (4) limited resource allocation to seed production and quality, which reduces the potential of seed-based restoration (Dayrell et al. 2016; Zanetti et al. 2020). These factors, isolated or in combination, cascade into recruitment bottlenecks, and largely explain slow natural regeneration after strong degradation/disturbance (Nerlekar & Veldman 2020). Regeneration from seeds to exogenous disturbance is naturally constrained in *campo rupestre*, especially in degraded areas (Dayrell et al. 2018; Arruda et al. 2021). Moreover, the high proportion of locally endemic species, for which knowledge of reproduction and propagation remains unknown, poses additional threats to restoration (Buisson et al. 2021).

Both iron ore opencast mining and quartzite quarrying are exogenous disturbances resulting from complex socioeconomic contexts and causing severe degradation and human conflicts. Innovative restoration frameworks are called upon, as mining activities expand both at the Espinhaço Range (Salles et al. 2019) and eastern Amazon (Souza-Filho et al. 2019) to meet the global demand for iron ore. Unfortunately, current attempts to restore *campo rupestre* have been done opportunistically, excluding stakeholders, without clear goals and metrics for monitoring success, and often overlooking scientific evidence, highlighting the need for the development of an overarching restoration framework. Therefore, we provide a set of

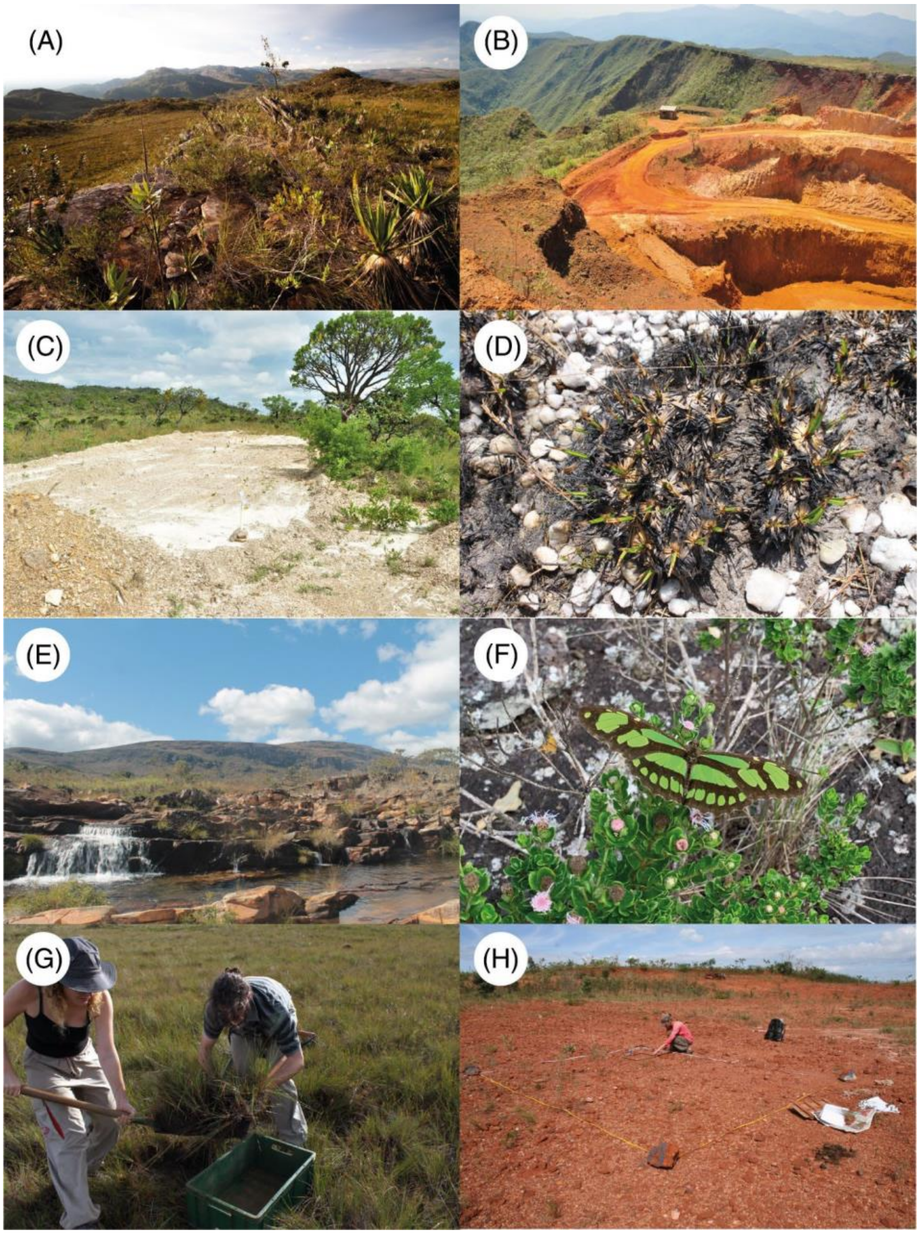

Figure 1. *Campo rupestre* vegetation, southeastern Brazil showing: (A) a mosaic of species-rich primary grasslands and scattered rocky outcrops with evergreen shrubs and sub-shrubs; (B) iron ore mining area at the Iron Quadrangle, Minas Gerais; (C) small quarries of soil exploitation with very low natural regenerationeven after a decade of abandonment; (D) endemic Eriocaulaceae species resprouting few weeks after fire; (E) scenic waterfall at the mountaintop of Espinhaçorange; (F) plant-pollinator interactions; (G) an active restoration experiment using topsoil transpositions; (H) long-term monitoring of areas under restoration.

guiding principles as a starting point to improve restoration science, policy, and practice. These guidelines should not be viewed as strict rules to guide on-site implementation, but as a living structure that can be adapted and expanded to different restoration contexts (Table 1; Fig. 2).

Principle 1: Include Socioeconomic Dimensions Into Restoration Frameworks

Including socioeconomic dimensions into restoration frameworks is key to preventing wasteful spending in programs that are likely to fail (Coleman et al. 2021). The lack of awareness and understanding of the ecosystem's ecological value and degradation impacts coupled with the limited availability and access to alternative sources of income for local communities often results in a striking dependence on destructive land-use practices in *campo rupestre* (Gontijo et al. 2018). Additionally, current restoration practices in *campo rupestre* largely and historically ignore socioecological dimensions and exclude local communities, often failing to develop appropriate, informed, and transparent prioritization decisions on restoration (Carvalho-Ribeiro et al. 2018; Chapman et al. 2021). By empowering community

Table 1. Principles to restore *campo rupestre*, a threatened tropical, megadiverse, nutrient-impoverished montane grassland, with a summary of the main problems and the practical implications/solutions for each principle.

Principle	*Problem*	*Practical Implications/Solutions*
Include socioeconomic dimensions	Local communities, decision-makers, and park managers have been long ignored across all stages of restoration frameworks in *campo rupestre*.	Inclusive restoration can generate multiple cobenefits by enhancing land-use management by local communities, generating income through community-based seed collection networks, and implementing participatory approaches to identify and map suitable areas for restoration.
Implement active restoration	*Campo rupestre* is slow to recover from exogenous disturbance, so natural regeneration is not an effective restoration strategy.	Natural regeneration is not a feasible or acceptable strategy, so active restoration is necessary to restore biodiversity and ecosystem services.
Keep low soil fertility	Many *campo rupestre* species are adapted to poor soils and do not form mycorrhizae because root specializations are more efficient in nutrient acquisition.	Keeping soil fertility low and avoiding fertilization is key to enhancing restoration success. However, restoring microbial communities is likely underappreciated as such organisms play key roles in reconstructing the substrate.
Restore disturbance regimes	Disturbance such as fires and grazing can be perceived as detrimental to restoration.	Implementing integrate fire management is expected to restore the natural disturbance regimes that species naturally adapted. The effect of grazers on *campo rupestre* should be studied before implementing rewilding with grazers.
Address genetic structure and adaptation potential	Genetic diversity of *campo rupestre* species is usually geographically structured resulting in highly differentiated populations.	Biological sourcing for restoration must take into account that dispersal limitation is a property of many *campo rupestre* species.
Restore geographically restricted and specialized ecological interactions	*Campo rupestre* harbors high levels of microendemics, and ecological networks are characterized by high specificity, turnover, and beta diversity.	Restoration strategies should combine the use of widespread species connecting modules and endemics that form the core of interaction networks.
Incorporate functional approaches	Projects overlooking functional diversity usually are unsuccessful in the long term because ecosystem functioning is not restored.	Species establishment and resilience should be promoted in the initial stages of the restoration programs by introducing species with traits that account for poor-nutrient content of degraded areas and for resprouting after disturbance.
Use seed-based restoration strategies to enhance biodiversity	Many species produce high rates of embryoless and nonviable seeds, with low seedling establishment rates.	Seed sowing should not be used primarily to increase soil cover, but rather to enhance biodiversity in later stages of the restoration program after resilience to fire has been achieved.
Translocation is inevitable	The expansion of mining pits threatens endemic species with small populations.	Recognize and embrace the multiple benefits of species translocation including the idea that translocations may be the only means of ensuring species survival in the wild.
Long-term monitoring is mandatory	Reassembly of high diversity communities in *campo rupestre* is extremely slow.	Monitoring programs should be planned for long-term spanning decades instead of years.

members as agents of change, inclusive restoration aims at building equitable participation and benefit sharing (Sigman & Elias 2021). We provide a few instances where embracing local communities have improved restoration outcomes in *campo rupestre*. First, traditional and sustainable farming system of the *sempre-viva* (endemic ornamental flowers in Eriocaulaceaeand Xyridaceae with high economic value) gatherers, which was recently recognized as a Globally Important Agricultural Heritage System (FAO 2022), and traditional fire management (Moura et al. 2019) can both inform land management and restoration. Second, community-based seed collection networks could be developed to supply restoration projects with native seeds and seedlings and generate income. Such networks consider local ecological knowledge during seed collection, preparation, and storage (Schmidt et al. 2019). Third, by implementing a participatory approach to identify and map strategic areas for restoration, decision-makers and stakeholders contributed significantly for effective and assessable mapping prioritization (Tourinho et al. 2023). Therefore, including socioeconomic dimensions at all stages of restoration frameworks is key to providing appropriate cobenefits to both people and nature (Fernandes et al. 2020; Choksi et al. 2023).

Principle 2: Implement Active Restoration

Natural regeneration has been suggested as a cost-effective strategy for tropical rainforest restoration but is unlikely to succeed in nutrient-poor ecosystems (Boxriker et al. 2022). In *campo rupestre*,

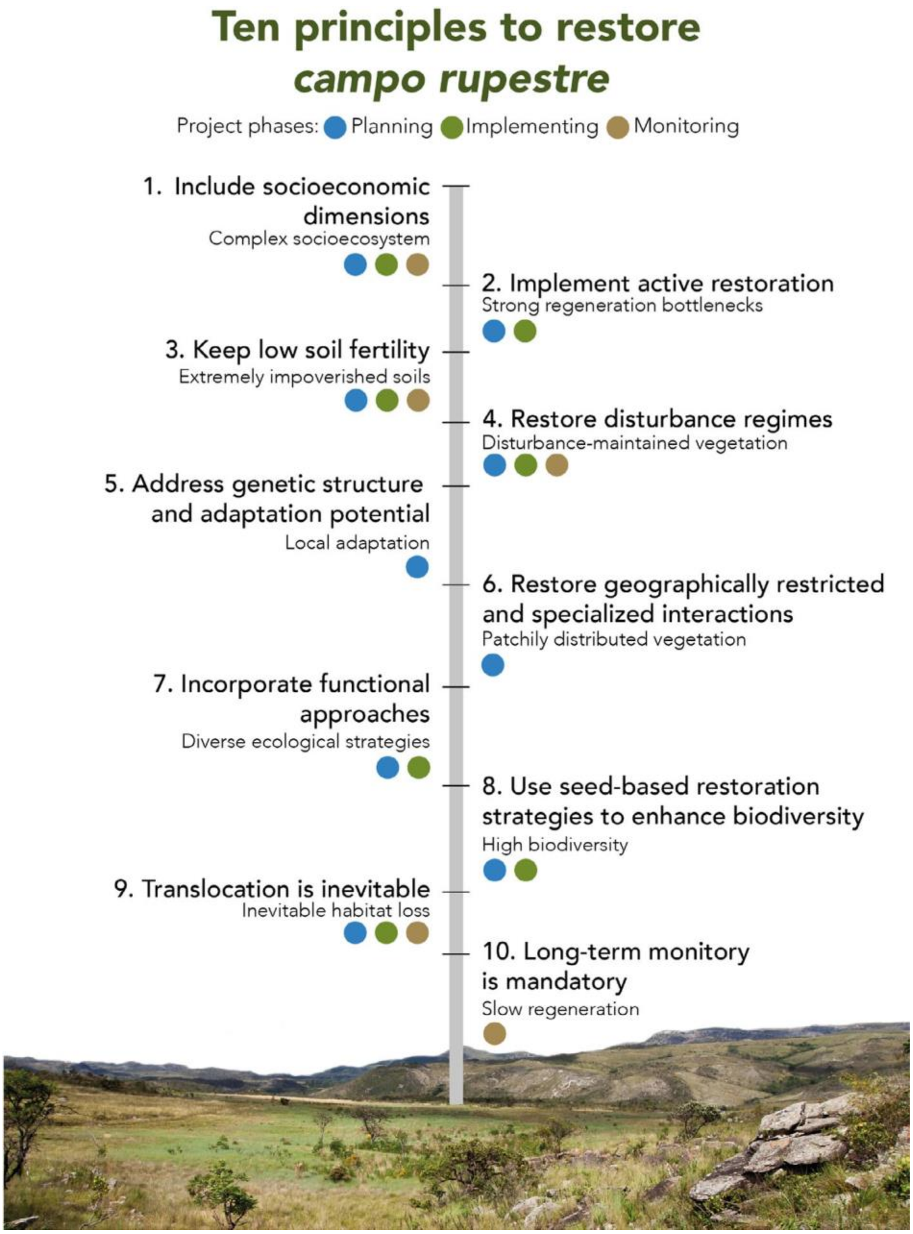

Figure 2. A conceptual framework depicting major challenges and principles to restore *campo rupestre* vegetation during the phases of planning, implementation, and monitoring.

the available data suggest that poor seed banks and poor seed quality are major bottlenecks for recruitment (Le Stradic et al. 2018). Second, most species lack specialized mechanisms for seed dispersal (Arruda et al. 2021), meaning that seeds have limited capacity to reach areas targeted for restoration. Third, many species are edaphic specialists (Giulietti et al. 2019), meaning that even if their seeds arrive in a target site (e.g. degraded with homogeneous and deeply altered soils), seedlings are unlikely to establish and survive due to narrow edaphic niche breadths. Lastly, even under unlikely events of a successful establishment, seedlings are slow-growing (Dayrell et al. 2018), underscoring a limited capacity to cover bare soils. Thus, regeneration bottlenecks chiefly explain why plant communities show insignificant signs of recovery after soil disturbance (Le Stradic et al. 2018), and why vegetation resulting from grassland degradation requires centuries or millennia to recover pre-disturbance richness (Nerlekar & Veldman 2020). Therefore, as for other nutrient-poor ecosystems (Hopper et al. 2021), we believe that active restoration is the most appropriate strategy to effectively restore *campo rupestre* and start promoting its resilience.

Principle 3: Maintain Low Soil Fertility

Campo rupestre is characterized by severely impoverished soils and slow-growth plants adapted to extreme resource limitation

(Oliveira et al. 2016). Iron mining operations result in significant alteration of the chemical soil properties in ironstone substrates in Eastern Amazon (Ramos et al. 2022). Keeping soil fertility low and avoiding fertilization is key to supporting native species requirements and preventing biological invasion (Barbosaet al. 2010; Silveira et al. 2020). However, the role of soil microbiota in enhancing the establishment of native species remains unclear. Microorganisms have recently been highlighted as potential game-changers in restoration (Coban et al. 2022). The root microbiome of endemic Velloziaceae from *campo rupestre* has the potential to promote phosphorus transport, mineralization, and solubilization (Camargo et al. 2023). Research on microorganisms of ferruginous substrates has opened important avenues in restoring substrate properties, such as developing microbial treatments to re-cement the crushed duricrust from iron ore mining and recreate soil conditions for habitat specialists (Gagen et al. 2020). While planting Fabaceae species should generally be applied with caution considering their potential to fertilize the soil and promote invasive species(e.g. Raghurama & Sankaran 2022), planting native ones in *campo rupestre* has been shown to keep soil fertility low enough while controlling invasive grasses (Nogueira et al. 2019). Arbuscular mycorrhizal fungi (AMF) on eroded quartzitic out-crops not only improve vegetation cover, but also increase nutri- ent availability (Medeiros et al. 2023). Thus, adding AMF androot microbiome should be used to adjust soil levels to predistur- bance conditions and to reestablish resource-acquisition strate-gies by native species as secretion of root exudates (Oliveiraet al. 2016).

Principle 4: Restore Disturbance Regime

In many systems, disturbances such as fire and grazing are often perceived and documented as detrimental to biological diversity. However, palaeoecological evidence indicates that open ecosystems have evolved under the influence of grazing and/or fire, and these disturbances have been essential for preventing woody encroachment (Baggio et al. 2021). Indeed, many old-growth tropical grasslands are maintained by endogenous disturbances (sensu Buisson et al. 2019) and often benefit from fire and grazing. Reestablishing the natural fire-vegetation feedbacks and increasing resilience to fire is important to promote long-term functional diversity, belowground C dynamics, and fire-induced flowering by adapting fire regimes to the state of the restored vegetation (Buisson et al. 2022). Fortunately, recent legislation changes promoting integrated fire management now allow for controlled fires to be used in restoration projects (Schmidt et al. 2018). Grazing as a management strategy for biodiversity, in turn, has been more recently explored in Brazil to reestablish vegetation dynamics (Baggio et al. 2021) and promote biodiversity (Durigan et al. 2022), depending on intensity. The American megafaunal extinctions in the Pleistocene have resulted in calls for reintroducing large mammal assemblages to restore the significant losses in ecosystem functions caused by defaunation (Galetti et al. 2018). However, Kolbek & Alves (2009) have demonstrated the detrimental effects of cattle grazing in *campo rupestre*, so further studies should be carried out on the type of animal species and stocking rate that *campo rupestre* could be adapted to. Restoring the disturbance regime with which *campo rupestre* has evolved in the last millions of years is expected to restore ecosystem functioning and promote biodiversity.

Principle 5: Address Genetic Structure and Adaptative Potential

Generalized plant transfer zones (GPTZs) rely on spatially congruent biotic and abiotic attributes to predict genetic structure and local adaptation, informing biological sourcing (Durkaet al. 2017; Gann et al. 2019). GPTZs are especially useful in areas characterized by low topographic and environmental heterogeneity (Massatti et al. 2020), as areas affected by glaciers or other large-scale past disturbances, where concordant phylogeographic patterns are usually observed (Taberlet et al. 1998). However, this is rarely the case for *campo rupestre*. Studies generally report extremely low between-population seed flow in *campo rupestre* regardless of climatic variations (Fiorini et al. 2019; Dantas-Queiroz et al. 2021), while others support Pleistocene climatic variation-mediated dispersal and isolation (Barres et al. 2019). Past demography processes are determinants for genetic structure and adaptative potential, thus when lacking genetic data, seed sourcing should consider the risk of both endogamic and exogamic depressions (Gann et al. 2019). Thus, to restore climate-resilient populations, we need to consider information on population evolution and demographic history, which are scarce in *campo rupestre*, but can be efficiently acquired using genomics (Dias et al. 2022; Walters et al. 2022; Fiorini et al. 2023). Population restoration is challenging and risky but moving forward toward modern approaches can help maintain the evolutionary potential in these dispersal-limited patchy communities (Gann et al. 2019).

Principle 6: Restore Geographically Restricted and Specialized Ecological Interactions

Ecological interactions are key for supporting ecosystem multifunctionality and overcoming regeneration filters (Funk 2021). Restoring ecological interactions to achieve resilience is especially challenging in heterogeneous ecosystems with remarkable biodiversity (Menz et al. 2011; Ritchie et al. 2021). Similarly to the *fynbos*, *campo rupestre* is characterized by plant species with patchy populations, where small-bodied pollinators access a range of species within a small area, have naturally small foraging ranges, and experience restricted dispersal, so that they remain in the relatively small, disjunct patches of suitable habitat. Consequently, interactions are usually locally limited, and networks are formed by tightly associated modules, with a marked high turnover of species and interactions (Carstensen et al. 2014). An additional challenge is the high level of specialization of interacting species in relation to their interactive partners at local and regional scales (Guerra et al. 2016). Such limitations mean that even if natural communities are successfully restored, long-term ecosystem functioning is expected to take impractical long periods of time. Therefore, to overcome the spatial limitations in species interactions and upscale restoration, species selection for restoration of ecological interactions should combine keystone, widespread plant species that can be introduced throughout large areas to connect communities at the landscape scale (Messeder et al. 2020), with endemics that form the core group of interactors at the local scale. Restoration should combine the reintroduction of both keystones to attract a wide diversity of ecological partners, provide functional redundancy, connection among modules, and endemics which form the core of plant–animal networks.

Principle 7: Incorporate Functional Approaches

Trait-based approaches in *campo rupestre* have an unexplored potential to support restoration projects (Giannini et al. 2017). First, seed-based restoration tends to focus on fast-growing species that allocate more resources to sexual reproduction and may exclude stress-tolerant (slow-growing) species that produce few seeds and regenerate via USOs (Giles et al. 2022). For example, projects aiming at restoring resilience to fire should prioritize USO-based strategies that ensure resprouting. Selecting fast-growing, fire-sensitive species may result in short-term faster soil cover, does not ensure resilience to endogenous disturbances (Giles et al. 2022), and is likely to result in impoverished and invaded communities in the long term (Giles et al. 2022). Second, soils on targeted sites have different water-holding capacities, different nutrient availability, and heavy metal toxicity. Hence, understanding water- and nutrient-acquisition (Oliveira et al. 2016; Rios et al. 2023) strategies should inform species selection aiming at promoting species coexistence and niche segregation. For example, mixtures of species containing different functional groups can promote diverse and resilient plant communities (Gastauer et al. 2022). Trait-based species selection can be implemented using functional trait coordination among plant organs to make more reliable inferences on species strategies and ecosystem functioning (Caminha-Paiva et al. 2021).

Principle 8: Use Seed-Based Strategies to Enhance Biodiversity

Seed-based strategies are widely used as a relatively low-cost, large-scale grassland restoration (D'Agui et al. 2022; Gerrits et al. 2023) and post-mining sites (Dalziell et al. 2022). However, seed-based strategies often show low success for *campo rupestre* (Le Stradic et al. 2014; Figueiredo et al. 2021), as indicated by low seedling emergence, and the prevalence of invasive species in the initial years of restoration. Failure in seed-based restoration strategies can be largely attributed to low seed set and quality (Dayrell et al. 2016) and low-density seed banks (Le Stradic et al. 2018). However, in topsoil translocation experiments without fertilization, fast-growing herbs dominated in the initial years, but were replaced over the following years by woody, slow-growing species (Onésimo et al. 2021). These results, coupled with recent synthesis showing that soil translocation can be an effective technique for restoring plant community diversity and composition (Gerrits et al. 2023), indicate promising results for seed-based restoration. We propose seed-based restoration to be implemented after resilience to fire has been achieved by restoring species with USOs. Seed-based strategies should aim at enhancing biodiversity and restore ecosystem functioning beyond resilience to disturbance.

Principle 9: Translocation Is Inevitable

Translocation (the deliberate transfer of plants or regenerative plant material from a natural population or an ex situ collection to a new location; Silcock et al. 2019) is increasingly becoming a standard mitigation approach for rare and endemic species. Translocation may be the only means of ensuring survival of species growing close to expanding mining pits (Zanettiet al. 2020). Still, translocation can only be effective if grounded in solid science to support the actions, outcomes, and balancing risk/benefit ratios (Commander 2018; Gastauer et al. 2021). Due to a poor understanding of species ecology, management and monitoring of both donor and recipient sites, translocation in *campo rupestre* is still considered a high-risk, high-cost strategy. Nevertheless, increasing mining expansion and climate change threats indicate that stakeholders will need to incorporate translocation methods in current and future restoration plans.

Principle 10: Long-Term Monitoring Is Mandatory

Long-term monitoring is critical for restoration projects because it provides many insights and supports adaptive management. Plant communities in *campo rupestre* are dominated by slow-growing, dispersal- and seed-limited species that usually regenerate through resprouting, and have slow recovery rates to exogenous disturbances. Consequently, community reassembly occurs on the scale of centuries to millennia, rather than years to decades (Nerlekar & Veldman 2020). Available data suggest that short-term monitoring fails to address changes in species survival, resource partitioning, recruitment (Gomes et al. 2018), vegetation cover, species richness, succession, community composition (Le Stradic et al. 2018), and population dynamics (Onésimo et al. 2021). Consequently, restoration trajectories in *campo rupestre* will only be reliable, realistic, and predictive if assessed in the long term and with an appropriate suite of indicators tailored for open ecosystems, despite associated costs.

Conclusions

The lack of general, practical, effective, and affordable strategies remains a major barrier to upscale global grassland restoration (Buisson et al. 2021). Here, we provide 10 principles to support restoration in *campo rupestre*, a particular type of grassland for which extreme resource- and seed-limitation pose additional barriers to ecological restoration. The challenges for *campo rupestre* restoration are especially high for mining sites, where soil and topsoil removal for mineral extraction dramatically changes the landscape and makes full ecological restoration unrealistic. Emerging technology including the reformation of iron-rich duricrusts (Gagen et al. 2020), cementation of residual minerals promoted by root exudates (Paz et al. 2020), and successful species reintroduction using different methods (Figueiredo et al. 2021; Gastauer et al. 2021; Onésimo et al. 2021) constitute reasons for optimism and higher levels of restoration aspirations than previously thought (Guedes et al. 2021).

Our principles are not exhaustive and should be viewed as an initial attempt to integrate the limited scientific evidence into a conceptual framework to steer both restoration policy and practice in *campo rupestre*, one of the most iconic grasslands worldwide (Bond 2019). Nevertheless, the principles represent the best available evidence supporting science and practice for the restoration of an ecosystem experiencing increasing mining pressure. To some extent, our principles can be useful for other megadiverse, fire-prone, and nutrient-poor ecosystems located in the Global South, where resilience has been compromised (Young et al. 2022), and regeneration bottlenecks need to be overcome (Standish & Hobbs 2010; Hopper et al. 2021).

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