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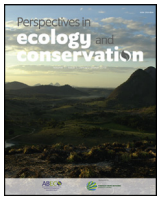

Essays and Perspectives

Biodiversity and ecosystem services in the Campo Rupestre: A road map for the sustainability of the hottest Brazilian biodiversity hotspot

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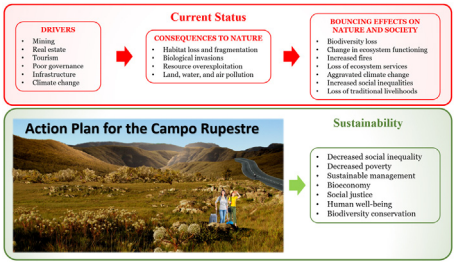
HIGHLIGHTS

- Campo Rupestre (CR) occurs in the ecotone Cerrado-Atlantic Forest biodiversity hotspots.
- CR epitomizes the conflicts between exploitative and sustainable socioeconomic models.
- We propose and describe the Action Plan for the Campo Rupestre (APCR).
- The APCR aims to reconcile the socioeconomic and environmental values in the CR.

GRAPHICAL ABSTRACT



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ABSTRACT

Global sustainability rests on a myriad of benefits provided by natural ecosystems that support human livelihoods and well-being, from biodiversity persistence to climate regulation. The undeniable importance of conserving tropical forests has drawn most of the conservation spotlight towards it. However, open ecosystems such as the Brazilian Campo Rupestre (rupestrian grassland), have been historically overlooked despite their high diversity and key associated ecosystem services. We highlight major current threats to the persistence of the Campo Rupestre emphasizing its ecological, social, cultural, geo-environmental, and economic importance. We call attention to the importance of the Campo Rupestre as a reservoir of biodiversity and ecosystem services and offer priority actions that resulted from discussions involving scientists, industry representatives, environmental managers, and other members of civil society. Proposed actions include efforts related to ecological restoration, sustainable ecotourism, protection of traditional ecological knowledge, identification of emerging research questions, and development of tailored public policies. Such issues are integrated into a framework that collectively represents a road map to safeguard the Campo Rupestre from further degradation and steer its historical overexploitation towards sustainable management. Safeguarding the future of non-forest biomes like this poses a challenge to current paradigms of nature conservation. By establishing priorities and guidelines, we propose an actionable plan, which we hope can support informed decision-making policy towards a sustainable use of the Campo Rupestre.

Introduction

Undoubtedly, the benefits provided by natural ecosystems, such as climate regulation, food security and water provision, represent a key asset of conservation science and practice (Pascual et al., 2017; Díaz et al., 2019). Although tropical forests have attained a forefront position, particularly due to their high biodiversity and carbon sequestration potential, there is an increasing need to appreciate the biodiversity and ecosystem services of other tropical ecosystems (Fernandes, 2016a; Overbeck et al., 2015; Veldman et al., 2015). Indeed, millions of people in Brazil and all over the world directly or indirectly depend on the services provided by non-forest ecosystems such as savannas and grasslands (Fernandes et al., 2018; Bond, 2019). Here, we focus on an integrative conservation strategy for the rupestrian grassland (hereafter *Campo Rupestre*, in Portuguese), a megadiverse ecosystem that provides essential services that are threatened by current exploitation models (Fernandes, 2016a; Fernandes et al., 2018). Unless actions are immediately taken to minimize threats, great losses to the Campo Rupestre ecosystem are expected in the next decades (Fernandes

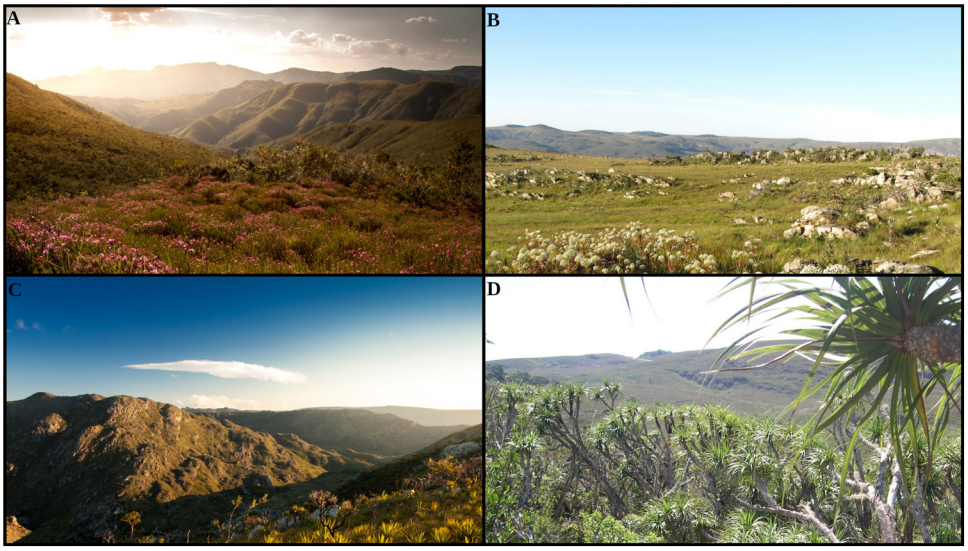

Fig. 1. Landscape and vegetation typical of the Campo Rupestre. (A) Wide shot of the Campo Rupestre highlands showing mixed woody and herbaceous communities on a rocky habitat. (B) Vast grasslands with rock outcrops dominated by flowering *Actinocephalus bongardii*. (C) Quartzitic gravel soil habitat immersed in a matrix of sandy and rocky grasslands. (D) Among rock outcrops, some larger species develop such as *Vellozia gigantea*. Photos by A. Gomes (A, C) and G.W. Fernandes (B, D).

et al., 2018). Our objective is to provide a goal-oriented strategy to shift the fate of the Campo Rupestre towards a more sustainable use. To this end, we first outline the biodiversity and conservation status of this ecosystem and analyze the feedback between its abiotic and biotic features and the current anthropogenic threats it is facing. Then, we provide a conceptual framework to foster sustainable use of the Campo Rupestre. Finally, we list a series of actions that we deem imperative to the constitution of an Alliance to Promote the Sustainability of the Campo Rupestre.

The local and global importance of the Campo Rupestre biodiversity and ecosystem services

The Campo Rupestre is characterized by a mosaic of open vegetation types. Its vegetation ranges from fire-prone natural grassland and savanna environments mixed with ericoid shrublands to scattered mountaintops, mostly associated with pre-Cambrian, extremely-impoverished quartzite, metarenites or ironstone outcrops (Fig. 1; Fernandes, 2016a). The Campo Rupestre occurs in mountains with ancient geological formations, residual cores of strongly weathered, folded, faulted, and eroded landmasses, later subjected to regional uplift during renewed tectonic events of lower magnitude (Schaefer et al., 2016). The Campo Rupestre is mostly associated with the Espinhaço Range, at the ecotone of the *Cerrado*, Atlantic Forest, and *Caatinga*. Disjunct, small areas are also patchily distributed across these biomes, in Minas Gerais, Bahia and Goiás states (Alves and Kolbek, 1994; Giulietti et al., 1997; Vasconcelos, 2011), in the Amazon forest including the Carajás Range and the tepuis, and in isolated mountains in the extreme west (Corumbá, Ricardo Franco Range) and northeastern Brazil (Fig. 2; Barbosa and Fernandes, 2016; Mota et al., 2018; Mattos et al., 2019; Zappi et al., 2019). The azonal, archipelago-like distribution of the Campo Rupestre sites created sky islands (altitudinal islands isolated by a continuous matrix of lowland vegetation), that promoted fast, geographically-structured diversification during the Pleistocene (Vasconcelos et al., 2020). The long-term isolation of populations and species derived from the sky island pattern (see De Bano et al., 1995) facilitated allopatric speciation resulting in the highest endemism rate among Brazilian vegetation types (more than 40% of plant species), with extremely high species turnover among sites (Echternacht et al., 2011; Neves et al., 2018; Colli-Silva et al., 2019; Mattos et al., 2019). The Campo Rupestre occupies an area of less than 0.8% of Brazil's surface area, yet it is home to more than 15% of its flora (Silveira et al., 2016). Altogether, these data suggest this ecosystem is the most critical hotspot of biodiversity in Brazil (Fernandes et al., 2014, 2018).

Species found in the Campo Rupestre evolved on extremely nutrient-poor soils (e.g., Abrahão et al., 2019; Fernandes, 2016b; Oliveira et al., 2016) derived from quartzites, sandstones and iron-rich rocks, whose weathering gives rise to sandy substrates and iron-oxide nodules (the latter being called *canga* in Portuguese; Ferrari et al., 2016). Its species are also adapted to markedly seasonal climates, which result in periodic droughts and fires (e.g., Silveira et al., 2016). Such strong environmental filters have favored the evolution of a vegetation with a functional signature characterized by slow-growth, specialized strategies for resource acquisition and conservation, low fecundity, and dispersal limitation (Negreiros et al., 2014; Oliveira et al., 2016; Dayrell et al., 2018; Le Stradic et al., 2018, see also Messias et al., 2012). The combination of these functional traits highlights Campo Rupestre's extremely low resilience to exogenous disturbances such as soil removal (e.g., Buisson et al., 2019; Fig. 3). Despite recent advances on the ecology of the Campo Rupestre plants, the ecology, evolution, and biogeography of animal life in this ecosystem are still poorly understood (Fernandes et al., 2014, 2018; Chaves et al., 2015; Ramos et al., 2019; Neves et al., 2020).

The scope of ecosystem services provided by the Campo Rupestre extends far beyond its area of occurrence, reaching some of the most populated areas of the country. Tens of millions of people benefit from the water supply, hydroelectric energy generation, ecotourism, medicinal plants, native fodder production, ecotourism, and belowground carbon storage provided by the Campo Rupestre ecosystem. The Campo Rupestre is home to small headwater streams, which often represent nearly 70% of total stream length in any hydrological unit or river basin (Benda et al., 2005). Mountaintops in Canastra and Espinhaço ranges are cradles of some of the most important rivers that provide water to millions of people living in the lowlands (Fernandes et al., 2018; Callisto et al., 2019; Rodrigues et al., 2019).

Furthermore, carbon located in underground storage organs of plant species from Campo Rupestre (Buisson et al., 2019) may represent globally relevant sources of carbon sequestration (see Jung et al., 2020). Additionally, the highest mycorrhiza diversity in the

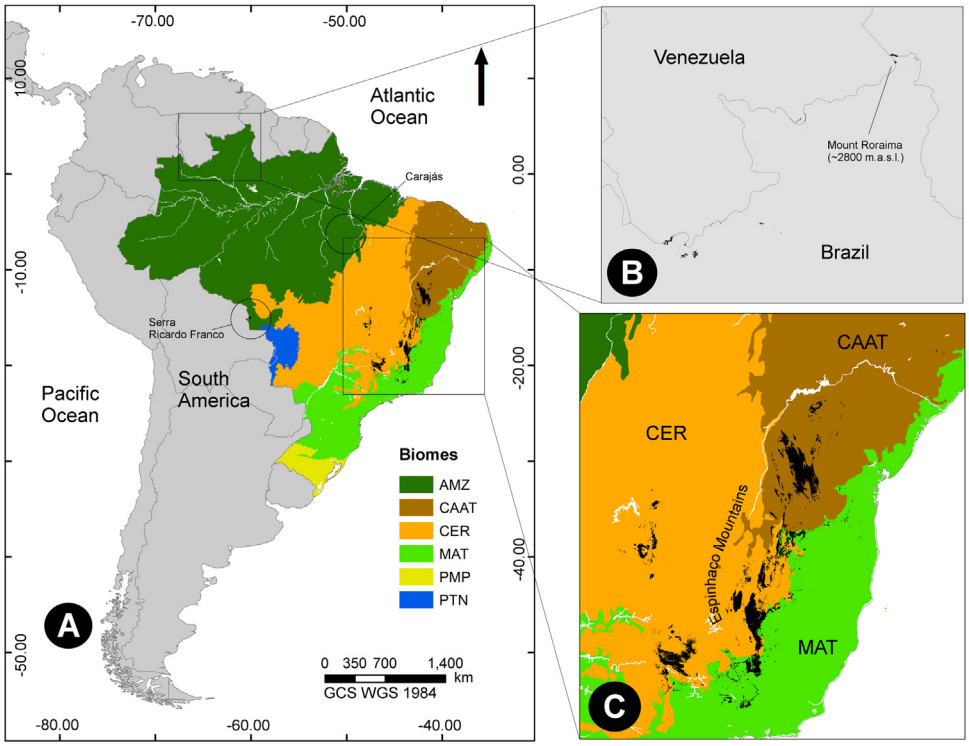

Fig. 2. The disjunct spatial distribution of the Campo Rupestre (black areas in the maps) across Brazilian Biomes. (A) South America focusing on the Brazilian territory. Two small portions of the Campo Rupestre are shown in panel A circles (Carajás and Serra Ricardo Franco), both contained in the AMZ. (B) A detailed panel of the Campo Rupestre portions at the Northern Brazilian region, and (C) at the Northeastern and Southeastern Brazilian regions. Biomes classification according to IBGE (2019): AMZ: Amazonia, CAAT: Caatinga, CER: Cerrado, MAT: Mata Atlântica, PMP: Pampa, PTN: Pantanal.

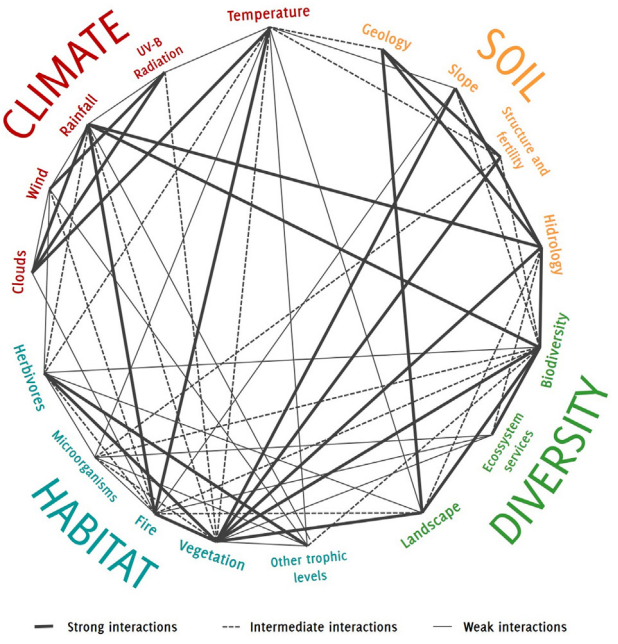

Fig. 3. Major and minor regional factors that sustain the Campo Rupestre ecosystem through their interactions. These factors are color-categorized according to their correspondent major driver (Microclimate, Habitat, Diversity, and Soil). The multiple interactions are represented through lines that were classified according to their significance in the ecosystem functioning (strong —, intermediate · · · · ·, and weak — interactions). For an in-depth discussion, including the interaction's strength, see Fernandes, 2016.

world is present in the Campo Rupestre (Carvalho et al., 2012; Oki et al., 2016) which can potentially help society to increase crop productivity and safeguard food security. Finally, this ecosystem also presents high aesthetic, religious, and cultural values (Giulietti and Pirani, 1988a; Resende et al., 2013).

Major threats

The activities that pose significant threats to the Campo Rupestre biodiversity and ecosystem services provision are numerous and are exemplified by ill planning of road construction and urban growth, uncontrolled mining, artisanal mining and ecotourism, afforestation with exotic trees (e.g., *Eucalyptus*), unplanned occupation and tourism, cattle overgrazing, overharvesting of ornamental species, and lack of governance (Barbosa et al., 2010; Fernandes et al., 2014; Ribas et al., 2016; Silveira et al., 2016; Batista et al., 2018; see reviews in Fernandes, 2016c; Fernandes et al., 2018). The history of degradation in the Campo Rupestre dates back to the early 17th century with gold mining, later on by diamond and gems, and in the last decades, iron and manganese extraction. Mining has contributed to increasing wealth in a global economy. It has also influenced and shaped the demographic, ethnic, cultural, artistic, social, and environmental aspects of Brazil (Neves et al., 2016). Among other activities that have relentlessly affected the functioning of the Campo Rupestre are urban growth and ecotourism. Altogether, these activities have been associated with many environmental and social conflicts (e.g., Morcatty et al., 2013; Neves et al., 2016; Fernandes et al., 2018; Pena et al., 2017; Zappi et al., 2019).

Unfortunately, existing protected areas are not large or efficient enough to protect the Campo Rupestre biodiversity and safeguard its ecosystem services (Pacheco et al., 2018). Currently, less than 10% of the total ecosystem area is protected (ca. 7720 km^2), which is far below the 17% target suggested by the Convention on Biological Diversity (DBD; https://www.cbd.int/sp/targets/) (Fernandes et al., 2018). Even more worryingly is the fact that many of these

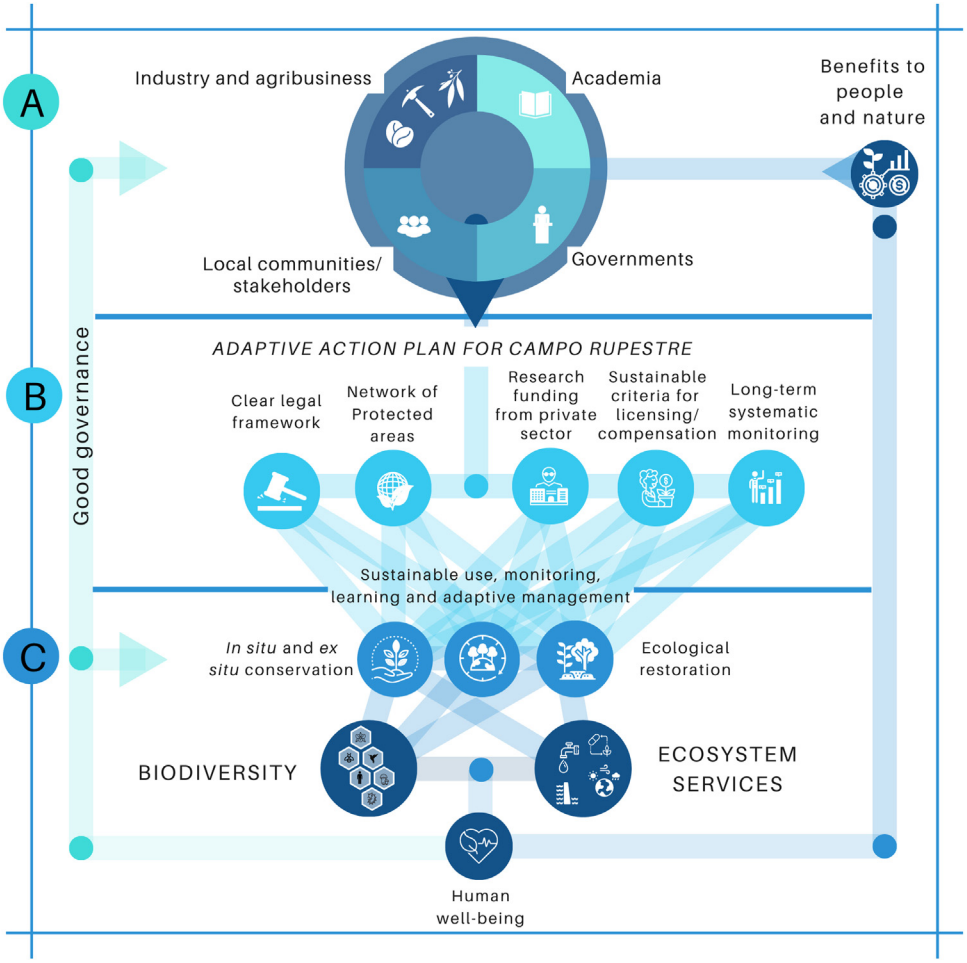

Fig. 4. A framework showing the conceptual basis of the Action Plan for the Campo Rupestre (APCR). The framework is divided into 3 sections: (A) major societal stakeholders, (B) proposed actions to support the APCR, and **C** expected outcomes after implementing the APCR strategies. The ultimate goal is to promote human well-being benefiting people and nature. The framework also illustrates feedback loops that positively influence the sustainable use of the Campo Rupestre.

protected areas have not been implemented effectively, the so-called "paper protected areas" (see Di Minin and Toivonen, 2015; Metzger et al., 2019). Furthermore, some of these areas experience significant land tenure issues, which has resulted in the disruption of livelihoods and retaliation by expropriated people against protected areas. Hence, we argue that the current protected area network is insufficient to secure the sustainability of the Campo Rupestre (Sonter et al., 2014; Pacheco et al., 2018). Thus, safeguarding biodiversity and ecosystem services associated with the Campo Rupestre requires the immediate engagement of various sectors of society, including local communities and indigenous people, government representatives, protected area managers, entrepreneurs, industry representatives, and the scientific community.

An alliance to promote the sustainability of the Campo Rupestre

We propose the guidelines to foster the constitution of an evidence-based Action Plan for the Conservation and Sustainable Management of the Biodiversity and Ecosystem Services of the Campo Rupestre (in short, Action Plan for the Campo Rupestre, APCR). We are aware that, despite being an urgent task, the plan needs to be discussed in its concrete and governance aspects. The APCR must be developed as a platform aiming to bring together stakeholders interested in the conservation and sustainable use of the Campo Rupestre, with the ultimate goal of reconciling socio-economic and environmental benefits (Fig. 4A). The proposal was discussed by a multidisciplinary group of experts during the XI Eugene Warming Lectures in Evolutionary Ecology (2017), hosted by the Federal University of Minas Gerais (UFMG). This group is formed by people intensely studying the ecology, evolution, and conservation of the Campo Rupestre for the last four decades. The group has been dealing with conservation conflicts, public policies discussions, and emerging scientific questions concerning the conservation and sustainable use of the Campo Rupestre. Online discussions followed the meeting, and here, we summarize the products of these discussions to further support the debate and the necessary multidisciplinary actions in conjunction with society.

While some conservation strategies for threatened plant species have recently been proposed by the Southern Espinhaço National Action Plan (Pougy et al., 2015), a broader approach to protect biodiversity beyond plants is still lacking (Monteiro et al., 2018). The following proposals are in consonance with and have been marked out for international sustainability agreements including the CBD, and The United Nations 2030 Agenda for Sustainable Development Goals (SDGs) and its associated targets. While many different models or initiatives exist addressing the SDGs, The Economics of Ecosystems and Biodiversity (TEEB) represents a global initiative focused on "making nature's values visible" that fits our goals for the Campo Rupestre. TEEB follows a structured approach to valuation that helps decision-makers recognize the wide range of benefits provided by ecosystems and biodiversity, demonstrate their values in economic terms and, where appropriate, capture those values in decision-making (Sukhdev, 2008). This initiative's

principal objective is to mainstream the values of biodiversity and ecosystem services into decision-making at all levels.

In the APCR, we offer a list of activities to develop public policies that are rooted in academia, local communities, industry, and government (see Fig. 4B for some examples). All social actors (including the private sector) share responsibilities and are represented in working groups that make collective decisions and recommendations. The integrative approach of the APCR is based on three strategies, (1) *in situ* and *ex situ* conservation, (2) sustainable use, monitoring, and management, and (3) ecological restoration.

One of the central tenets of the APCR is the development of precise quantitative indicators and unequivocal definitions for long-term monitoring, supporting conservation strategies and restoration success. Systematic monitoring during all stages is key for effective policy development and the implementation of all the actions and measures (see Kollmann et al., 2016). Each conservation strategy has its value and purpose, but *in situ* conservation is the preferred choice. *Ex situ* conservation is also relevant and should be used whenever possible to aid the achievement of the conservation goals. Ecological restoration of the Campo Rupestre is crucial for securing ecosystem services and biodiversity. While recent studies have shown good progress for the Campo Rupestre (reviewed in Fernandes et al., 2016, see also Gomes et al., 2015), there are still numerous challenges to be overcome for tropical grasslands in general, as shown by Buisson et al. (2019).

Although the APCR proposed here still needs to be debated into its concrete actions, given governance and practical contingencies, we argue that it is mandatory that all steps and decisions of the APCR should be guided by scientific evidence. A shift towards the effective application of science is necessary to support an adaptive flow of processes. The successful implementation of the APCR is expected to protect biodiversity and ecosystem services, which in turn, would provide positive, long-lasting benefits to our society (see Fig. 4C for some examples of the expected outcomes).

Public policies

Current rates of land-use changes in the Campo Rupestre remain largely unknown, due to poor legal requirements for monitoring. Yet, drastic impacts have been documented since the discovery of gold and diamonds in the early 18th century and the increase of iron ore mining from World War II onwards (Neves et al., 2016). Unlawful occupation of rural areas for leisure and farming, unregulated expansions of quartzite quarrying mining in Diamantina plateau, but also the plantation of eucalyptus, coffee and mango on shallow soils and peatlands, the irregular occupation of areas around springs are just a few examples of poorly documented by land use changes that put the long-term conservation of the Campo Rupestre at risk. Public policies concerning the Campo Rupestre should address the following:

i. A TEEB-kind of analysis and economic valuation of the Campo Rupestre biodiversity and ecosystem services to support the decision-making process stakeholders' claims of the wide range of benefits provided by ecosystems and biodiversity;
ii. Tightening and enforcing current regulation coupled with the development of new and specific legislation that takes into account the features of non-forest vegetation and includes the most endangered species within the Campo Rupestre. This can be achieved through each regional State Council for Environmental Policy, which are collegiate groups of people of a consultative normative and deliberative nature. Thus, within the scope of their competence, they can put out normative proposals on the sustainable management and quantitative indicators for long-term monitoring, conservation, and restoration strategies (e.g. art. 214, §7 and art. 57 of State Law MG 20.922/2013). Such Councils must discuss specific legislation with technical-academic support to review the criteria for licensing and financial compensation (Miola et al., 2019, see also Fernandes et al., 2020);
iii. Despite the widely acknowledged key role of science in supporting evidence-based decision makings, resources available for research funding in Brazil are still scant (Fernandes et al., 2017). We argue that a fairly reasonable alternative is that private investments could provide additional funding for conservation research projects. We propose the development of legal instruments that make it possible to support long-term scientific studies by reverting part of the financial resources obtained from compensations, royalties from the mining sector, and conservation fees charged upon the sustainable tourism exploration of protected areas. A potential financial source is the Compensation for Mineral Resources Exploitation (*Compensação Financeira pela Exploração de Recursos Minerais* – CFEM in Portuguese), which comprises funds paid by the mining companies to the Federal Government that are partially returned to the municipalities that host the mining activities (Brazilian federal laws 7990/1990 and 8001/1990 and Decree 01/1991). Unfortunately, the current overly centralized approach by the Federal Government states that between ca. 35% of the CFEM funds remain at the federal and state level.
iv. The creation of legal instruments for payment for ecosystem services (PES) prioritizing water and food security, biodiversity conservation and carbon storage. The PES can follow examples such as the water farmers in the municipality of Extrema, Minas Gerais, Brazil (Programa Produtores de Água) or PES programs related to the dam disaster in Mariana, Minas Gerais, Brazil;
v. The establishment of policies and development of protocols to monitor and minimize the impact of infrastructure-related threats including biological invasions and soil erosion (Barbosa et al., 2010);
vi. The establishment of an open-data network of biodiversity inventories of the Campo Rupestre biota to support environmental assessment studies. This platform should also integrate and strengthen scientific collections from different institutions and provide online, georeferenced information of all records;
vii. More sustainable mining to mitigate the trade-offs between mining, environmental and socio-economic aspects (Neves et al., 2016; Collins and Kumral, 2019). To achieve this, a set of actions should be fostered. For example, the revision of legislation to better compensate municipalities from which minerals were extracted is desirable as long as legal measures are set to guide the allocation of these resources. These financial resources could be used by local governments to stimulate sustainable development in their municipalities, including actions to conserve or increase the provision of key ecosystem services to the region, mitigate the social impacts from mining activities, as well as create positive synergies among mining and other sectors such as social assistance and education (Barbieri et al., 2014; Neves et al., 2016). Considering that the mining taxes are not enough to compensate for the loss of ecosystem services (Domingues et al., 2012), social and environmental costs of mining should be included in the accounting of the municipalities with mining activities (e.g. by using the Genuine Progress Indicator: Berik, 2020). Incorporating the socio-economic dimension in the decision-making process is a paramount step towards more sustainable mining. In addition, all societal sectors should be encouraged to establish new protected areas aiming to improve *in situ* conservation of the Campos Rupestre and complement the protected areas network managed by the government.

Conservation, management and restoration of biodiversity and ecosystem services

Restricted geographical distribution, small populations, and habitat specificity, together with increasing human-caused disturbances, result in a high level of threatened species (Pougy et al., 2015). For the long-term conservation of the Campo Rupestre biodiversity and its associated ecosystem services, activities should include:

i. Development and maintenance of existing long-term monitoring programs to secure the conservation of endangered species involving both *in situ* and *ex situ* conservation strategies;
ii. Stimulation and nurturing of programs for the research, registration and protection of cultural heritage, especially those linked with the traditional knowledge of ecosystem management by communities that allow current biodiversity conservation (Gavin et al., 2015);
iii. The mapping and establishment of biodiversity baselines programs to monitor the effect of global change drivers of biodiversity, and the provision of ecosystem services (Fernandes et al., 2018; Callisto et al., 2019; Chase et al., 2020);
iv. Identification of (bio)indicators to monitor landscape integrity;
v. The assessment of the ecological integrity of the Campo Rupestre's current protected areas and its effectiveness for the current and future safeguarding of its biodiversity and ecosystem services;
vi. The allocation of priority areas for the further expansion of current protected areas to achieve a more effective landscape planning supporting the sustainable development and international protection of the Campo Rupestre, taking into account, through a multi-stakeholder committee, the various conservation attributes, as well as the demands of indigenous and local communities and of industry representatives;
vii. The development and implementation of integrated fire management protocols to maintain biodiversity in heterogeneous landscape mosaics, where fire-prone plant communities often coexist with fire-sensitive communities (Figueira et al., 2016; Batista et al., 2018; Rodrigues et al., 2019).
viii. The development of strategies for integrating local communities in long-term programs of environmental education including citizen science programs, schools, land-owners, tourism companies, and religious communities, stimulating the participation and employment of local people as agents of education (França et al., 2019).

Regional socio-economic development and territorial planning

Many of the Campo Rupestre sites occur in areas with low potential for large-scale agriculture, due to adverse environmental circumstances and poor soil conditions (Almada et al., 2016). As a consequence, human populations have derived their livelihood mainly from family agriculture and cattle ranching, hunting, extraction of minerals and harvesting of ornamental plants, including endangered species (Giulietti et al., 1988b; Almada et al., 2016). However, cattle grazing associated with anthropogenic fires (Batista et al., 2018), *Eucalyptus* plantations (Ribas et al., 2016), and agriculture have expanded into the Campo Rupestre sites. Silviculture and agriculture rely on fertilizers, liming, and pesticides, dramatically affecting the nutrient-poor Campo Rupestre soils, facilitating biological invasions and changing the natural fire regimes (Barbosa et al., 2010).

Targeted use of the Campo Rupestre biological resources can help to reconcile conservation and economic goals in the long-term if well planned under a solid scientific basis. In this regard, the implementation of an economic system supported by the use of renewable resources in a sustainable matter such as the bioeconomy may represent a potential strategy for achieving sustainability in this ecosystem (Aguilar et al., 2019; Ladu et al., 2020). From the perspective of socio-economic development of the Campo Rupestre and the maintenance of its natural capital, it is necessary to:

i. Develop bioeconomy models consistent with the conservation and sustainable use of ecosystem resources according to the livelihoods of local communities (Aguilar et al., 2019);
ii. Promote the unification of urban and regional master plans of all municipalities that encompass the Campo Rupestre vegetation for the better planning of urban development, and increase landscape connectivity;
iii. Evaluate the current status of *Cadastro Ambiental Rural* - (Rural Environmental Registry, in English) and take legal measures to develop strategies towards normalizing and implementing Permanent Preservation Areas and Legal Reserves in private areas of municipalities covered by the Campo Rupestre to some extent.
iv. Modelling multiple off-setting scenarios aiming at reaching a target of no-net biodiversity loss for impacting activities (Sonter et al., 2014) to guide decision making.
v. Identify social, cultural and economic characteristics of traditional communities including *quilombolas* (i.e. communities of people who resisted the Brazilian slave regime; maroons in English) and work in tandem with their ethnoecological knowledge to reduce overharvesting.

Towards sustainable ecotourism

Although mountains are desired destinations for tourism, demanded by visitors seeking scenic beauty and adventure, unplanned tourism expansion has been a source of high environmental impact to the Campo Rupestre (Fernandes, 2016c). While an essential attribute for tourists who visit the Campo Rupestre is related to recreation (Resende et al., 2017), overexploitation of the visited areas leads to landscape degradation in its trails, waterfalls, washes, rivers, and roadsides. For this reason, a positive agenda for the development of sustainable ecotourism requires:

i. Development of quantitative indicators for monitoring and regulating tourism impacts;
ii. Determination of carrying capacity of touristic sites in protected areas;
iii. Development of local environmental education initiatives, including participatory monitoring (citizen science) with local school students and teachers;
iv. Development of scientific training of tourist guides and locals, sharing benefits and knowledge;
v. Promotion of science outreach activities to tourists and local communities (e.g. bird watching and wildlife tourism that combine income generation and conservation).

Towards engaged scientific and local communities

Increasing the engagement of the scientific community in the decision-making process is vital to ensure evidence-based, long-lasting, sustainable solutions. Increasing the engagement of local communities is important as well to ensure on the one hand that their needs are being properly addressed and on the other hand to incorporate their traditional and valuable knowledge in the

decision-making process. Unbalanced political and administrative representativeness is likely to fail in reconciling the interests of various stakeholders. To improve the outcomes, we need to:

1. Broaden academic representation in watershed committees, advisory councils of protected areas and councils in environmental and regulatory agencies;
2. Encourage the articulation of academia with environmental agencies, decision-makers, and legislators through courses, technical training, unified events, and technical-scientific cooperation agreements.
3. Create mechanisms to assure the representation and empowerment of local communities.

Emerging scientific issues and technical knowledge

Although the number of studies on the Campo Rupestre has increased significantly in the last three decades (reviews in Fernandes et al., 2018; Morellato and Silveira, 2018), severe knowledge gaps persist. A number of emerging priority questions can be identified that are fundamental for informed-decisions that will benefit both nature and people associated with the Campo Rupestre.

Relevant actions to fill knowledge gaps include the formulation of calls for funding long-term multi- and interdisciplinary scientific research by private and government funding agencies. Pressing issues include: (1) a solid inventory and quantification of ecosystem services provided by the Campo Rupestre, (2) climate change monitoring showing the impacts, vulnerability, and necessary adaptations, (3) fire monitoring and management, (4) assessments of land-use conversion, (5) determination of ecosystem resilience, (6) the development of scientific knowledge in ecological restoration, (7) inventorying biodiversity on poorly sampled areas, (8) implementation of *ex situ* conservation protocols for threatened taxa, (9) integration of traditional and scientific ecological knowledge for community-based management, 10) promotion of environmental justice and public participation through bioeconomy models.

Synthesis and the way forward

The APCR may provide the spark to trigger a large-scale and innovative program on bioeconomy in Brazil, in light of the increasing anthropogenic threat and current erosion of the natural and cultural heritage of the Campo Rupestre. The measures and synergic actions of the APCR can contribute to change the current Brazilian conservation paradigm and protect one of its most threatened ecosystems. Such actions have the potential to increase socioeconomic benefits through income generation and the creation of employment of ecologically and economically viable alternative activities. The APCR proposes a series of concrete measures that, if implemented and integrated, can lead to a positive change in land and water use models, thus allowing the sustainable use/development of the Campo Rupestre and its associated people.

The APCR suggests specific mechanisms to advance and synergize the engagement among stakeholders to enact specific legislation leading to the conservation and sustainable use of the Campo Rupestre. While we acknowledge that the proposed actions do not cover all relevant needs, we believe the APCR can be an effective science-based platform to develop and implement further adaptive changes needed. We posit that this integrative alliance can be a cornerstone for the conservation and sustainable use of the Campo Rupestre that will ultimately benefit both nature and people.

Conflict of interest

None declared.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.pecon.2020.10.004.

References

Abrahão, A., de Brito Costa, P., Lambers, H., Andrade, S.A.L., Sawaya, A.C.H.F., Ryan, M.H., Oliveira, R.S., 2019. Soil types select for plants with matching nutrient-acquisition and use traits in hyperdiverse and severely nutrient-impoverished campos rupestres and cerrado in Brazil Central. J. Ecol. 107, 1302–1316, http://dx.doi.org/10.1111/1365-2745.13111.

Aguilar, A., Twardowski, T., Wohlgemuth, R., 2019. Bioeconomy for sustainable development. Biotechnol. J. 14, 1–11, http://dx.doi.org/10.1002/biot.201800638.

Almada, E.D., Anaya, F.C., Monteiro, F.T., 2016. The people of the mountains: the biocultural heritage of the Espinhaço Range in Minas Gerais State, Brazil. In: Fernandes, G.W. (Ed.), Ecology and Conservation of Mountaintop Grasslands in Brazil. Springer, Switzerland, pp. 479–499, http://dx.doi.org/10.1007/978-3-319-29808-5_20.

Alves, R.J.V., Kolbek, J., 1994. Plant species endemism in savanna vegetation on table mountains (campo rupestre) in Brazil. Vegetation (Plant Ecol.) 113, 125–139, http://dx.doi.org/10.1007/BF00044230.

Barbieri, A.F., Domingues, E.P., Monte-Mór, R.L.M., Santos, F.B.T., Rigotti, J.I.R., Rodrigues, B.H.M., Tonucci, J., Neto, O.B., Cortezzi, F., 2014. Plano regional estratégico em torno de grandes projetos minerários no médio Espinhaço. FUNDED, Belo Horizonte, Brazil.

Barbosa, N.P.U., Fernandes, G.W., Carneiro, M.A.A., Junior, L.A.C., 2010. Distribution of non-native invasive species and soil properties in proximity to paved roads and unpaved roads in a quartzitic mountainous grassland of southeastern Brazil (rupestrian fields). Biol. Invas. 12, 3745–3755, http://dx.doi.org/10.1007/s10530-010-9767-y.

Barbosa, N.P.U., Fernandes, G.W., 2016. Rupestrian grassland: past, present and future distribution. In: Fernandes, G.W. (Ed.), Ecology and Conservation of Mountaintop Grasslands in Brazil. Springer, Switzerland, pp. 531–544, http://dx.doi.org/10.1007/978-3-319-29808-5_22.

Batista, E.K.L., Russell-Smith, J., França, H., Figueira, J.E.C., 2018. An evaluation of contemporary savanna fire regimes in the Canastra National Park, Brazil: Outcomes of fire suppression policies. J. Environ. Manage. 205, 40–49, http://dx.doi.org/10.1016/j.jenvman.2017.09.053.

Benda, L., Hassan, M.A., Church, M., May, C.L., 2005. Geomorphology of steepland headwaters: the transition from hillslopes to channels. J. Am. Water Resour. Assoc. 41, 835–851, http://dx.doi.org/10.1111/j.1752-1688.2005.tb03773.x.

Berik, G., 2020. Measuring what matters and guiding policy: an evaluation of the Genuine Progress Indicator. Int. Lab. Rev. 159, 71–94, http://dx.doi.org/10.1111/ilr.12153.

Bond, W.J., 2019. Open Ecosystems: Ecology and Evolution Beyond the Forest Edge. Oxford University Press, UK, 175p.

Buisson, E., Le Stradic, S., Silveira, F.A.O., Durigan, G., Overbeck, G.E., Fidelis, A., Fernandes, G.W., Bond, W.J., Hermann, J.-M., Mahy, G., Alvarado, S.T., Zaloumis, N.P., Veldman, J.W., 2019. Resilience and restoration of tropical and subtropical

grasslands, savannas, and grassy woodlands. Biol. Rev. 94, 590–609, http://dx.doi.org/10.1111/brv.12470.
Callisto, M., Solar, R., Silveira, F.A.O., Saito, V.S., Hughes, R.M., Fernandes, G.W., Gonçalves-Júnior, J.F., Leitão, R.P., Massara, R.L., Macedo, D.R., Neves, F.S., Alves, C.B.M., 2019. A Humboldtian approach to mountain conservation and freshwater ecosystem services. Front. Environ. Sci. 7, 1–12, http://dx.doi.org/10.3389/fenvs.2019.00195.
Carvalho, F., De Souza, F.A., Carrenho, R., de Souza Moreira, F.M., da Conceição Jesus, E., Fernandes, G.W., 2012. The mosaic of habitats in the high-altitude Brazilian rupestrian fields is a hotspot for arbuscular mycorrhizal fungi. Appl. Soil Ecol. 52, 9–19, http://dx.doi.org/10.1016/j.apsoil.2011.10.001.
Chaves, A.V., Freitas, G.H., Vasconcelos, M.F., Santos, F.R., 2015. Biogeographic patterns, origin and speciation of the endemic birds from eastern Brazilian mountaintops: a review. Syst. Biodivers. 13, 1–16, http://dx.doi.org/10.1080/14772000.2014.972477.
Chase, J.M., Jeliazkov, A., Ladouceur, E., Viana, D.S., 2020. Biodiversity conservation through the lens of metacommunity ecology. Ann. N. Y. Acad. Sci. 1469, 86–104, http://dx.doi.org/10.1111/nyas.14378.
Collins, B., Kumral, M., 2019. Environmental sustainability, decision-making, and management for mineral development in the Canadian Arctic. Int. J. Sustain. Dev. World, 1–13, http://dx.doi.org/10.1080/13504509.2019.1684397.
Colli-Silva, M., Vasconcelos, T.N., Pirani, J.R., 2019. Outstanding plant endemism levels strongly support the recognition of *campo rupestre* provinces in mountaintops of eastern South America. J. Biogeogr. 46, 1723–1733, http://dx.doi.org/10.1111/jbi.13585.
Dayrell, R.L., Arruda, A.J., Pierce, S., Negreiros, D., Meyer, P.B., Lambers, H., Silveira, F.A.O., 2018. Ontogenetic shifts in plant ecological strategies. Funct. Ecol. 32, 2730–2741, http://dx.doi.org/10.1111/1365-2435.13221.
De Bano, L.F., Ffolliott, P.F., Ortega - Rubio, A., Gottfried, G.J., Hamre, R.H., Edminster, C.B. (Eds.), 1995. Biodiversity and Management of the Madrean Archipelago: The Sky Islands of Southwestern United States and Northwestern Mexico. General Technical Report, RM – GTR – 264. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, 669 p.
Díaz, S., Settele, J., Brondízio, E.S., Ngo, H.T., Agard, J., Arneth, A., Balvanera, P., Brauman, K.A., Butchart, S.H.M., Chan, K.M.A., Garibaldi, L.A., Ichii, K., Liu, J., Subrmanian, S.M., Midgley, G.F., Miloslavich, P., Molnár, Z., Obura, D., Pfaff, A., Polasky, S., Purvis, A., Razzaque, J., Reyers, B., Chowdhury, R.R., Shin, Y.-J., Visseren-Hamakers, I., Wilis, K.J., Zayas, C.N., 2019. Pervasive human-driven decline of life on Earth points to the need for transformative change. Science 366, 1–10, http://dx.doi.org/10.1126/science.aax3100.
Di Minin, E., Toivonen, T., 2015. Global protected area expansion: creating more than paper parks. BioScience 65, 637–638, http://dx.doi.org/10.1093/biosci/biv064.
Domingues, S.A., Karez, C.S., Biondini, I.V.F., Andrade, M.A., Fernandes, G.W., 2012. Economic environmental management tools in the Serra do Espinhaço Biosphere Reserve. J. Sustain. Dev. 5, 180–191.
Echternacht, L., Trovó, M., Oliveira, C.T.C.T., Pirani, J.R., 2011. Areas of endemism in the Espinhaço Range in Minas Gerais, Brazil. Flora 206, 782–791, http://dx.doi.org/10.1016/j.flora.2011.04.003.
Fernandes, G.W. (Ed.), 2016a. Ecology and Conservation of Mountaintop Grasslands in Brazil. Springer, Switzerland.
Fernandes, G.W., 2016b. The megadiverse rupestrian grassland. In: Fernandes, G.W. (Ed.), Ecology and Conservation of Mountaintop Grasslands in Brazil. Springer, Switzerland, pp. 3–14.
Fernandes, G.W., Barbosa, N.P.U., Negreiros, D., Paglia, A.P., 2014. Challenges for the conservation of vanishing megadiverse rupestrian grasslands. Perspect. Ecol. Conserv. 2, 162–165, http://dx.doi.org/10.1016/j.ncon.2014.08.003.
Fernandes, G.W., Barbosa, N.P.U., Alberton, B., Barbieri, A., Dirzo, R., Goulart, F., Guerra, T.J., Morellato, L.P.C., Solar, R., 2018. The deadly route to collapse and the uncertain fate of the rupestrian grasslands. Biodivers. Conserv. 27, 2587–2603, http://dx.doi.org/10.1007/s10531-018-1556-4.
Fernandes, G.W., Toma, T.S.P., Angrisano, P., Overbeck, G., 2016. Challenges in the restoration of quartzitic and ironstone rupestrian grasslands. In: Fernandes, G.W. (Ed.), Ecology and Conservation of Mountaintop Grasslands in Brazil. Springer, Switzerland, pp. 449–477.
Fernandes, G.W., 2016. The shady future of the rupestrian grassland: major threats to conservation and challenges in the Anthropocene. In: Fernandes, G.W. (Ed.), Ecology and Conservation of Mountaintop Grasslands in Brazil. Springer, Switzerland, pp. 545–561.
Fernandes, G.W., Bahia, T.O., Almeida, H.A., Conceiça˜o, A.A., Loureiro, C.G., Luz, G.R., Neves, A.C.O., Oki, Y., Pereira, G.C.N., Pirani, J.R., Viana, P.L., Negreiros, D., 2020. Floristic and functional identity of rupestrian grasslands as a subsidy for environmental restoration and policy. Ecol. Com. 43, 1–8, http://dx.doi.org/10.1016/j.ecocom.2020.100833.
Fernandes, G.W., Vale, M.M., Overbeck, G.E., Bustamante, M.M.C., Grelle, C.E.V., Bergalo, H.G., Magnusson, W.E., Akama, A., Alves, S.A., Amorim, A., Araújo, J., Barros, C.F., Bravo, F., Carim, M.J.V., Cerqueira, R., Collevatti, R.G., Colli, G.R., Cunha, C.N., D'Andrea, P.S., Dianese, J.C., Diniz, S., Estrela, P.C., Fernandes, M.R.M., Fontana, C.S., Giacomin, L.L., Gusmão, L.F.P., Juncá, F.A., Lins, A.C.B., Lopes, C.R.A.S., Lorini, M.L., Queiroz, L.P., Malabarba, L.R., Marimon, B.S., Marimon-Junior, B., Marques, M.C.M., Martinelli, B.M., Martins, M.B., Medeiros, H.F., Menin, M., Morais, P.B., Muniz, F.H., Neckel-Oliveira, S., Oliveira, J.A., Oliveira, R.P., Pedroni, F., Penha, J., Podgaiski, L.R., Rodrigues, D.J., Scariot, A., Silveira, L.F., Silveira, M., Tomas, W.M., Vital, M.J.S., Pillar, V.D., 2017. Dismantling Brazil's science threatens global biodiversity heritage. Perspect. Ecol. Conserv. 15, 239–243, http://dx.doi.org/10.1016/j.pecon.2017.07.004.
Ferrari, L.T., Schaefer, C.E.G.R., Fernandes, R.B.A., Mendonça, B.A.F., Gjorup, D.F., Corrêa, G.R., Senra, E.O., 2016. Thermic and hydric dynamics of ironstone (Canga) and quartzite rupestrian grasslands in the Quadrilátero Ferrífero: the ecological importance of water. In: Fernandes, G.W. (Ed.), Ecology and Conservation of Mountaintop Grasslands in Brazil. Springer, Switzerland, pp. 71–85, http://dx.doi.org/10.1007/978-3-319-29808-5_4.
Figueira, J.E.C., Ribeiro, K.T., Ribeiro, M.C., Jacobi, C.M., França, H., de Oliveira Neves, A.C., Conceição, A.A., Mourão, F.A., Souza, J.M., Miranda, C.A.K., 2016. Fire in rupestrian grasslands: plant response and management. In: Fernandes, G.W. (Ed.), Ecology and Conservation of Mountaintop Grasslands in Brazil. Springer, Switzerland, pp. 415–448, http://dx.doi.org/10.1007/978-3-319-29808-5_18.
França, J.S., Solar, R., Hughes, R.M., Callisto, M., 2019. Student monitoring of the ecological quality of neotropical urban streams. Ambio 48, 867–878, http://dx.doi.org/10.1007/s13280-018-1122-z.
Gavin, M.C., McCarter, J., Mead, A., Berkes, F., Stepp, J.R., Peterson, D., Tang, R., 2015. Defining biocultural approaches to conservation. Trends Ecol. Evol. 30, 140–145, http://dx.doi.org/10.1016/j.tree.2014.12.005.
Gomes, V.M., Negreiros, D., Carvalho, V., Fernandes, G.W., 2015. Growth and performance of rupestrian grasslands native species in quartzitic degraded areas. Neotrop. Biol. Conserv. 10, 159–168, http://dx.doi.org/10.4013/nbc.2015.103.06.
Giulietti, A.M., Pirani, J.R., 1988a. Patterns of geographic distribution of some plant species from the Espinhaço Range, Minas Gerais and Bahia, Brazil. In: Vanzolini, P.E., Heyer, W.R. (Eds.), Proceedings of a Workshop on Neotropical Distribution Patterns. Academia Brasileira de Ciências, Rio de Janeiro, pp. 39–69.
Giulietti, A.M., Pirani, J.R., Harley, R.M., 1997. Espinhaço range region, eastern Brazil. In: Davis, S.D., Heywood, V.H. (Eds.), Centres of Plant Diversity: A Guide and Strategy for their Conservation. IUCN Publication Unity, Cambridge, pp. 397–404.
Giulietti, N., Giulietti, A.M., Pirani, J.R., Menezes, N.L., 1988b. Estudos de sempre-vivas: importância econômica do extrativismo em Minas Gerais, Brasil. Acta Bot. Bras. 1, 179–194, http://dx.doi.org/10.1590/S0102-33061987000300018.
Jung, M., et al., 2020. Areas of global importance of terrestrial biodiversity, carbon and water. Bioarkiv, http://dx.doi.org/10.1101/2020.04.16.021444.
Kollmann, J., Meyer, S.T., Bateman, R., Conradi, T., Gossner Jr, M.M., Mendonça, M.S., Fernandes, G.W., Koch, C., Muller, S.C., Oki, Y., Overbeck, G.E., Paterno, G.B., Rosenfield, Toma, T.S.P., Weisser, W.W., 2016. Integrating ecosystem functions into restoration ecology-recent advances and future directions. Rest. Ecol. 24, 722–730.
Ladu, L., Imbert, E., Quitzow, R., Morone, P., 2020. The role of the policy mix in the transition toward a circular forest bioeconomy. Forest Policy Econ. 110, 1–17, http://dx.doi.org/10.1016/j.forpol.2019.05.023.
Le Stradic, S., Buisson, E., Fernandes, G.W., Morellato, L.P.C., 2018. Reproductive phenology of two contrasting neotropical mountain grasslands. Appl. Veg. Sci. 29, 15–24, http://dx.doi.org/10.1111/jvs.12596.
Mattos, J.S., Camargo, M.G.G., Morellato, L.P.C., Batalha, M.A., 2019. Plant phylogenetic diversity of tropical mountaintop rocky grasslands: local and regional constraints. Plant Ecol. 220, 1119–1129, http://dx.doi.org/10.1007/s11258-019-00982-5.
Messias, M.C.T.B., Leite, M.G.P., Meira-Neto, J.A.A., Kozovits, A.R., 2012. Fitossociologia de campos rupestres quartzíticos e ferruginosos no Quadrilátero Ferrífero, Minas Gerais. Acta Bot. Bras. 26, 230–242, http://dx.doi.org/10.1590/S0102-33062012000100022.
Metzger, J.P., Bustamante, M.M., Ferreira, J., Fernandes, G.W., Librán-Embid, F., Pillar, V.D., Prist, P.R., Rodrigues, R.R., Vieira, I.C., Overbeck, G.E., 2019. Why Brazil needs its legal reserves. Perspect. Ecol. Conserv. 17, 91–103, http://dx.doi.org/10.1016/j.pecon.2019.07.002.
Miola, D.T.B., Marinho, A.P., Dayrell, R.L.C., Silveira, F.A.O., 2019. Silent loss: misapplication of an environmental law compromises conservation in a Brazilian biodiversity hotspot. Perspect. Ecol. Conserv. 17, 84–89, http://dx.doi.org/10.1016/j.pecon.2019.04.001.
Monteiro, L.M., Machado, N., Martins, E., Pougy, N., Verdi, M., Martinelli, G., Loyola, R.D., 2018. Conservation priorities for the threatened flora of mountaintop grasslands in Brazil. Flora 238, 234–243, http://dx.doi.org/10.1016/j.flora.2017.03.007.
Morcatty, T.Q., El Bizri, H.R., Carneiro, H.C.S., Biasizzo, R.L., Alméri, C.R.O., Silva, E.S., Rodrigues, F.H.G., Figueira, J.E.C., 2013. Habitat loss and mammalian extinction patterns: are the reserves in the Quadrilátero Ferrífero, southeastern Brazil, effective in conserving mammals? Ecol. Res. 28, 935–947, http://dx.doi.org/10.1007/s11284-013-1076-3.
Morellato, L.P.C., Silveira, F.A.O., 2018. Plant life in campo rupestre: new lessons from an ancient biodiversity hotspot. Flora 238, 1–10, http://dx.doi.org/10.1016/j.flora.2017.12.001.
Mota, N.F.O., Watanabe, M.T.C., Zappi, D.C., Hiuri, A.L., Pallos, J., Viveiros, R.S., Giulietti, A.M., Viana, P., 2018. Amazon canga: the unique vegetation of Carajás revealed by the list of seed plants. Rodriguesia 69, 1435–1488, http://dx.doi.org/10.1590/2175-7860201869336.
Negreiros, D., Le Stradic, S., Fernandes, G.W., Rennó, H.C., 2014. CSR analysis of plant functional types in highly diverse tropical grasslands of harsh environments. Plant Ecol. 215, 379–388, http://dx.doi.org/10.1007/s11258-014-0302-6e.
Neves, A.C.O., Barbieri, A.F., Pacheco, A.A., de Moura Resende, F., Braga, R.F., Azevedo, A.A., Fernandes, G.W., 2016. The human dimension in the Espinhaço

Mountains: land conversion and ecosystem services. In: Fernandes, G.W. (Ed.), Ecology and Conservation of Mountaintop Grasslands in Brazil. Springer, Switzerland, pp. 501–530, http://dx.doi.org/10.1007/978-3-319-29808-5_21.
Neves, D.M., Dexter, K.G., Pennington, T., Bueno, M.L., Miranda, P.L.S., Oliveira-Filho, A.T., 2018. Lack of floristic identity in campos rupestre – a hyperdiverse mosaic of rocky montane savannas in South America. Flora 238, 24–31, http://dx.doi.org/10.1016/j.flora.2017.03.011.
Neves, F.S., da Silva, P.G., Solar, R., Nunes, C.A., Beirão, M.V., Brant, H., Castro, F.S., Dáttilo, W., Guevara, R., Fernandes, G.W., 2020. Habitat generalists drive nestedness in a tropical mountaintop insect metacommunity. Biol. J. Linnean Soc., blaa059, http://dx.doi.org/10.1093/biolinnean/blaa059.
Oki, Y., Goto, B.T., Jobim, K., Rosa, L.H., Ferreira, M.C., Coutinho, E.S., Xavier, J.H.A., Carvalho, F., Moreira, F.M.S., Souza, F.A., Berbara, R.L.L., Fernandes, G.W., 2016. Arbuscular mycorrhiza and endophytic fungi in ruspestrian grasslands. In: Fernandes, G.W. (Ed.), Ecology and Conservation of Mountaintop Grasslands in Brazil. Springer, Switzerland, pp. 157–179, http://dx.doi.org/10.1007/978-3-319-29808-5_8.
Oliveira, R.S., Abrahão, A., Pereira, C., Teodoro, G.S., Brum, M., Alcantara, S., Lambers, H., 2016. Ecophysiology of *campos rupestre*'s plants. In: Fernandes, G.W. (Ed.), Ecology and Conservation of Mountaintop Grasslands in Brazil. Springer, Switzerland, pp. 227–272, http://dx.doi.org/10.1007/978-3-319-29808-5_11.
Overbeck, G.E., Vélez-Martin, E., Scarano, F.R., Lewinsohn, T.M., Fonseca, C.R., Meyer, S.T., Müller, S.C., Ceotto, P., Dadalt, L., Durigan, G., Ganade, G., Gossner, M.N., Guadagnin, D.L., Lorenzen, K., Jacobi, C.M., Weisser, W.W., Pillar, V.D., 2015. Conservation in Brazil needs to include non-forest ecosystems. Divers. Distrib. 21, 1455–1466, http://dx.doi.org/10.1111/ddi.12380.
Pacheco, A.A., Neves, A.C., Fernandes, G.W., 2018. Uneven conservation efforts compromise Brazil to meet the Target 11 of Convention on Biological Diversity. Perspect. Ecol. Conserv. 16, 43–48, http://dx.doi.org/10.1016/j.pecon.2017.12.001.
Pascual, U., Balvanera, P., Díaz, S., Pataki, G., Roth, E., Stenseke, M., Watson, R.T., Dessane, E.B., Islar, M., Kelemen, E., Maris, V., Quaas, M., Subramanian, S.M., Wittmer, H., Adlan, A., Ahn, S., Al-Hafedh, Y.S., Amankwah, E., Asah, S.T., Berry, P., Bilgin, A., Breslow, S.J., Bullock, C., Cáceres, D., Daly-Hassen, H., Figueroa, E., Golden, C.D., Gómez-Baggethun, E., González-Jiménez, D., Houdet, J., Keune, H., Kumar, R., Ma, K., May, P.H., Mead, A., O'Farrell, P., Pandit, R., Pengue, W., Pichis-Madruga, R., Popa, F., Preston, S., Pacheco-Balanza, D., Saarikoski, H., Strassburg, B.B., Belt, M.v.d., Verma, M., Wickson, F., Yagi, N., 2017. Valuing nature's contributions to people: the IPBES approach. Curr. Opin. Environ. Sustain. 26, 7–16, http://dx.doi.org/10.1016/j.cosust.2016.12.006.
Pena, J.C.C., Goulart, F., Fernandes, G.W., Hoffmann, D., Leite, F.S., dos Santos, N.B., Soares-Filho, B., Sobral-Souza, T., Vancine, M.H., Rodrigues, M., 2017. Impacts of mining activities on the potential geographic distribution of eastern Brazil mountaintop endemic species. Perspect. Ecol. Conserv. 15, 172–178, http://dx.doi.org/10.1016/j.pecon.2017.07.005.
Pougy, N., Verdi, M., Martins, E., Loyola, R., Martinelli, G., Rapini, A., Quinet, A., Marcato, A.C., Lima, A.M.S., Jack, A., Scatigna, A.V., Martins, A.B., Carneiro, A.C.G.S., Loeuille, B.F.P., Ferreira Júnior, C.A., Lima, C.M., Takeuchi, C., Jacobi, C.M., Maurenza, D., Zappi, D., Salviano, D.A., Dalcin, E., Costa, F.N., Hurbath, F., Wimmer, F., Fernandes, F.M., Toledo, F., Ávila, G.C., Fernandes, G.W., Ferreira, I.L., Prado, J., Nakajima, J.N., Oliveira, J.A., Rando, J.G., Lovo, J., Guimarães, L.C., Martins, L.G.M., Andrade, L.E., Bedê, L.C., Lima, L.G., Menini Neto, L., Devecchi, M.F., Santos, M.A., Fernandes, M.G.C., Jorge, M.R.U., Assis, M.C., Andrade, M.A., Roque, N., Mota, N.F.O., Machado, N., Bernardes, N., Ferreira, P.L., Sano, P.T., Fiaschi, P., Viana, P.L., Almeida, R.F., Forzza, R.C., Harley, R.M., Romero, R., Silva, S.R., Cavalcanti, T.B., Giorni, V.T., 2015. Plano de Ação Nacional para a conservação da flora ameaçada de extinção da Serra do Espinhaço Meridional. Instituto de Pesquisas Jardim Botânico do Rio de Janeiro, Centro Nacional de Conservação da Flora (CNCFlora), Andrea Jakobsson Estúdio, Rio de Janeiro.
Ramos, E.K.S., Magalhães, R.F., Marques, N.C.S., Baêta, D., Garcia, P.C.A., Santos, F.R., 2019. Cryptic diversity in Brazilian endemic monkey frogs (Hylidae, Phyllomedusinae, Pithecopus) revealed by multispecies coalescent and integrative approaches. Mol. Phylogenet. Evol. 132, 105–116, http://dx.doi.org/10.1016/j.ympev.2018.11.022.
Resende, F., Fernandes, G.W., Andrade, D.C., Néder, H.D., 2017. Economic valuation of the ecosystem services provided by a protected area in the Brazilian Cerrado: application of the contingent valuation method. Braz. J. Biol. 77, 762–773, http://dx.doi.org/10.1590/1519-6984.21215.
Resende, F.M., Fernandes, G.W., Coelho, M.S., 2013. Economic valuation of plant diversity storage service provided by Brazilian rupestrian grassland ecosystems. Braz. J. Biol. 73, 709–716, http://dx.doi.org/10.1590/S1519-69842013000400005.
Ribas, R.P., Caetano, R.M., Gontijo, B.M., de Azevedo Xavier, J.H., 2016. Afforestation in the rupestrian grasslands: the augmenting pressure of *Eucalyptus*. In: Fernandes, G.W. (Ed.), Ecology and Conservation of Mountaintop Grasslands in Brazil. Springer, Switzerland, pp. 395–414, http://dx.doi.org/10.1007/978-3-319-29808-5_17.
Rodrigues, E.L., Jacobi, C.M., Figueira, J.E.C., 2019. Wildfires and their impact on the water supply of a large neotropical metropolis: a simulation approach. Sci. Total Environ. 651, 1261–1271, http://dx.doi.org/10.1016/j.scitotenv.2018.09.289.
Schaefer, C.E., Cândido, H.G., Corrêa, G.R., Nunes, J.A., Arruda, D.M., 2016. Soils associated with rupestrian grasslands. In: Fernandes, G.W. (Ed.), Ecology and Conservation of Mountaintop Grasslands in Brazil. Springer, Switzerland, pp. 55–69, http://dx.doi.org/10.1007/978-3-319-29808-5_3.
Silveira, F.A.O., Negreiros, D., Barbosa, N.P.U., Buisson, E., Carmo, F.F., Carstensen, D.W., Conceição, A.A., Cornelissen, T.G., Echternacht, L., Fernandes, G.W., Garcia, Q.S., Guerra, T.J., Jacobi, C.M., Lemos-Filho, J.P., Le Stradic, S., Morellato, L.P.C., Neves, F.S., Oliveira, R.S., Schaefer, C.E., Viana, P.L., Lambers, H., 2016. Ecology and evolution of plant diversity in the endangered campo rupestre: a neglected conservation priority. Plant Soil 403, 129–152, http://dx.doi.org/10.1007/s11104-015-2637-8.
Sonter, L.J., Barrett, D.J., Soares-Filho, B.S., 2014. Offsetting the impacts of mining to achieve no net loss of native vegetation. Conserv. Biol. 28, 1068–1076, http://dx.doi.org/10.1111/cobi.12260.
Vasconcelos, M.F., 2011. O que são campos rupestres e campos de altitude nos topos de montanha do leste do Brasil? Rev. Bras. Bot. 34, 241–246, http://dx.doi.org/10.1590/S0100-84042011000200012.
Sukhdev, P., 2008. The Economics of Ecosystems & Biodiversity: An Interim Report. European Union Commission for the Environment, Brüssel, European Community.
Vasconcelos, T.N.C., Alcantara, S., Andrino, C.O., Forest, F., Reginato, M., Simon, M.F., Pirani, J.R., 2020. Fast diversification through a mosaic of evolutionary histories characterizes the endemic flora of ancient Neotropical mountains. Proc. R. Soc. B 287, 1–10, http://dx.doi.org/10.1098/rspb.2019.2933.
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., 2015. Where tree planting and forest expansion are bad for biodiversity and ecosystem services. Bioscience 65, 1011–1018, http://dx.doi.org/10.1093/biosci/biv118.
Zappi, D.C., Moro, M.F., Walker, B., Meagher, T., Viana, P.L., Mota, N.F.O., Watanabe, M.T.C., Nic Lughadha, E., 2019. Plotting a future for Amazonian canga vegetation in a campo rupestre context. PLoS ONE 14, 1–19, http://dx.doi.org/10.1371/journal.pone.0219753.