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ORIGINAL PAPER

The deadly route to collapse and the uncertain fate of Brazilian rupestrian grasslands

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Abstract Rupestrian grasslands are biodiverse, evolutionary old vegetation complexes that harbor more than 5000 species of vascular plants and one of the highest levels of plant endemism in the world. Growing on nutrient–impoverished soils and under harsh environmental conditions, these mountaintop ecosystems were once spared from major human interventions of agriculture and intensive cattle ranching. However, in Brazil, rupestrian grasslands have experienced one of the most extreme land use changes among all Brazilian ecosystems, suffering from ill policies leading to intense mining activities, uncontrolled tourism, and unplanned road construction. Indeed, the discovery of large mineral reserves, the adoption of ineffective conservation policies, and, going forward, climate change, are

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threatening this hyper-diverse ecosystem. Here, we shed light on the severe threats imposed by land-use changes in this ecosystem, modeling its future distribution under different scenarios. We uncover a catastrophic forecast that, if not halted, will lead to the loss of 82% of this unique ecosystem in the future, impacting ecosystem services at regional scales, including water and food security potentially affecting more than 50 million persons.

Keywords Biodiversity · *Campo rupestre* · Cerrado · Espinhaço mountains · Mining · Sustainability

Introduction

Conservation efforts in Brazil should be a matter of discussion across all its biomes, but it is undeniable that these efforts have tended to focus on forested ecosystems (Santos et al. 2011; Overbeck et al. 2015; Fernandes 2016a). Non-forest areas, such as the rupestrian grasslands ("*campo rupestre*"), remain underappreciated and, consequently, under severe anthropogenic threat (Fernandes et al. 2014; Fernandes 2016b). These areas harbor a diversity of organisms that rivals forests in terms of number of species and exceeds them in the proportion of endangered flora. Distributed mainly within the Cerrado domain (savanna) in the upper parts of the Espinhaço mountain range (the second largest mountain chain in South America after the Andes), this highly heterogeneous herbaceous/shrubby vegetation is a mosaic of rocky outcrops embedded in a matrix of sandy and stony grasslands, seasonal wet grasslands, springs, and occasional forest patches on mountaintops (Fig. 1) (for a review see Fernandes 2016a). Rupestrian grasslands evolved in ancient landscapes (Barbosa and Fernandes 2016) shaped by quartzitic and ferruginous rocks (Schaefer et al. 2016). These geologically old landscapes and evolutionary ancient vegetation complexes cover an area of ca. 83,000 km^2 and harbor great biodiversity, which includes more than 5000 species of vascular plants and one of the highest levels of endemism in the world (Alves et al. 2014; Silveira et al. 2016).

Brazilian rupestrian grasslands' unique biota has long-attracted the attention of several scientists. Early in the XIX century, many prominent European naturalists, including Martius, Spix, Langsdorff, Saint-Hilaire, Lund, and Warming, explored the region covered by this ecosystem (Warming 1892; Vasconcelos et al. 2008; Fernandes 2016a; Mügge et al. 2016; Lüttge 2017). The work by Eugen Warming in the transitional area between cerrado and the rupestrian grasslands—a seasonally dry forest transition region (1863–1866) at the base of the Espinhaço mountain range—provided the scenario whereby the first books on plant ecology (Warming 1892, 1895) were forged. Biodiversity in this ecosystem began to be catalogued more intensively by biologists in the 1960s and, although scattered in space and time, their assessments compiled a large number of species for the fauna and flora of the Espinhaço mountain range, with hundreds of new species being described over the past 50 years. The most recent species compilations for the Espinhaço range highlight this region as an important center of biological diversity and plant endemism (Giulietti et al. 1997; Echternacht et al. 2011; Fernandes 2016a; Silveira et al. 2016), fish (Alves et al. 2008), frogs (Leite et al. 2008), birds (Vasconcelos et al. 2008; Chaves et al. 2015), galling insects (Fernandes and Santos 2014), and arbuscular mycorrhizal fungi (Carvalho et al. 2012; Coutinho et al. 2015), among many other groups.

Even after decades of study, the rate of new species discovery in Brazilian rupestrian grasslands is still very high (Fig. 2). For instance, an average of 12 new plant and 4 new

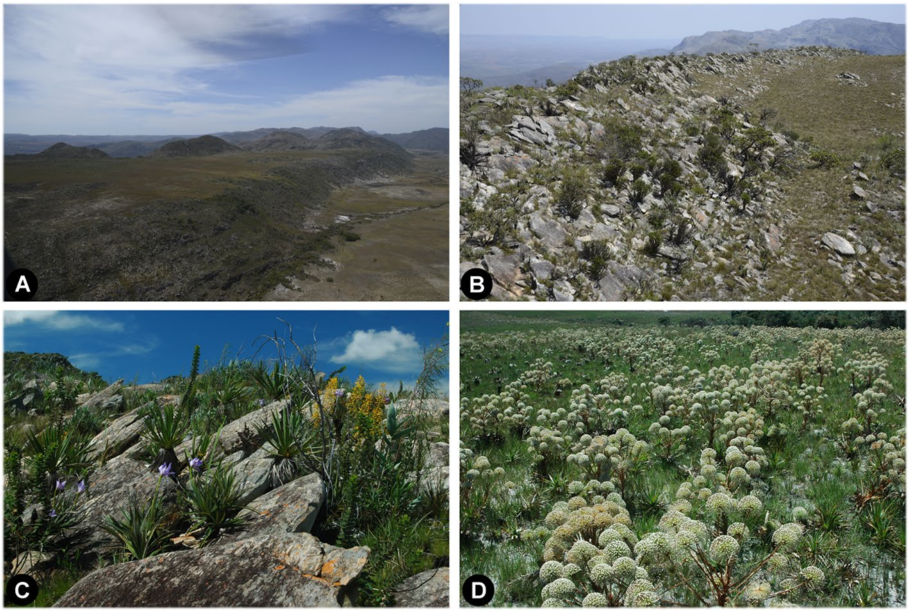

Fig. 1 Aerial view of rupestrian grasslands on quartzitic soils in Serra do Cipó, southeastern Brazil. The landscape is composed of a mosaic of habitats, mostly sandy grasslands, rough terrain with stony grasslands, rocky outcrops, and forests on humid slopes and valleys (**a**). Rocky outcrops are perhaps the most prominent habitat with large rocks interspersed with woody vegetation. Their erosion gives rise to the adjacent stony or sandy grasslands, dominated by different species (**b**). Detailed view of the speciose rocky grassland habitats, where highly endemic Velloziaceae, Melastomataceae, Eriocaulaceae, forbs and grasses thrive (**c**). A patch of the endemic *Paepalanthus robustus* (Eriocaulaceae) (**d**)

animal species were described per year in the Espinhaço mountain range from 2005 to 2014. At least 118 new plant species in 27 families, and 26 new vertebrate species, comprising 11 frogs, 8 lizards, 4 birds, 2 snakes and one mammal, were described within a single decade (Tables S1, S2). Two recently described species, the rodent *Calassomys apicalis* (Pardiñas et al. 2014) and the ovenbird *Cinclodes espinhacensis* (Freitas et al. 2012) (Fig. S1a), illustrate the singularity of most of the new species described. Also, among the 11 new arthropods described, the iridescent blue spider, *Pterinopelma sazimai* (Fig. S1b), and the flesh-fly mimicking weevil, *Timorus sarcophagoides* (Fig. S1c), are particularly remarkable. All these species are often rare, associated to mountaintop grasslands, patchily distributed and have become known to science under some degree of threat. Recent studies also indicate that rupestrian grasslands are home to ca. 25% of the world's described species of mycorrhizae (Carvalho et al. 2012) and that 19 new species of these fungi are in line to be described to science (Coutinho et al. 2015).

Such high levels of diversity and endemism in rupestrian grasslands have been argued to be the result of strong environmental filters, such as nutrient–deprived soils, pronounced seasonality, and climatic variability related to wide altitudinal and latitudinal gradients (Fernandes et al. 2014; Negreiros et al. 2014; Fernandes 2016c). Indeed, not only new species, but also novel interactions are being found in these ecosystems, since harsh conditions and poor soils have driven striking adaptations of the endemic organisms. For example, the carnivorous plant *Philcoxia minensis* exhibits a unique prey-capture strategy among plants,

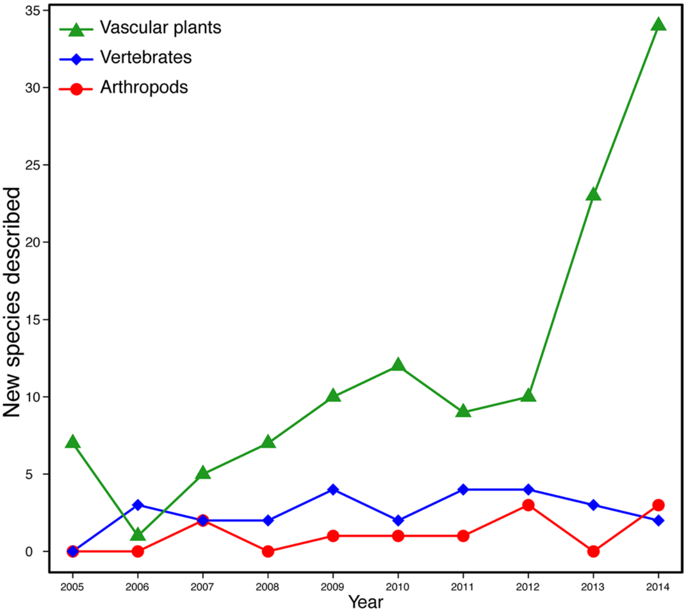

Fig. 2 Rate of new species discovery in Brazilian rupestrian grasslands between 2005 and 2014. See text and Table S1 for details

being able to trap and digest nematodes in its underground adhesive leaves (Figs. S1d, S1e) (Pereira et al. 2012; see also Oliveira et al. 2016). Additionally, the protocarnivorous plant *Paepalanthus bromelioides* (Fig. S1f) evolved the capacity of its leaves to derive nitrogen from both spiders' prey carcasses and feces, while roots uptake nitrogen from associated termite mounds (Nishi et al. 2013). Clearly, mechanisms and processes responsible for high species diversity in the Espinhaço range are numerous and vary across taxa (see Morellato and Silveira 2018 and references therein). The synergy among environmental filters, geographic barriers related to altitudinal variation and species interactions represent the most important forces leading to the vast array of adaptations and, likely, speciation in its fauna and flora (Fernandes 2016c). Furthermore, the high endemism and species richness intrinsic to rupestrian grasslands could have been shaped by interglacial microrefugia, which might have maintained buffered microclimates derived from topographic idiosyncrasies, which prevented extinctions (Barbosa et al. 2015).

Therefore, while representing less than 1% of the Brazilian territory, rupestrian grasslands shelter about 17% of the country's estimated plant biodiversity and ca. 46% of that of the Cerrado, the second largest biome in South America (Fernandes et al. 2016a). However, the unfortunate reality is that, despite its exuberant biodiversity, the rupestrian grasslands are experiencing one of the most intense land use alterations among all Brazilian ecosystems (Fernandes et al. 2014; Sonter et al. 2014a; Fernandes 2016b; Pena et al. 2017). The loss of species and habitats, particularly on mountaintops, is of major relevance due to the potentially dire cascading effects that would result in the loss of species interactions, ecosystem connectivity and environmental services (Epps et al. 2006; Spehn et al. 2010).

Given the continental relevance of this mountain region and the lack of appropriate protection of its natural heritage, our aim in this paper is to cast some light on and draw attention to the major threats imposed by land use and climate change to rupestrian grasslands. By analyzing the prevailing threats to this ecosystem and then modeling its temporal dynamics, we aim to examine its projected distribution and to identify emergent patterns of potential future expansion or contraction and to determine climatically stable areas important for biodiversity conservation and ecosystem services (i.e., where conditions will remain suitable for the persistence of rupestrian grasslands). Furthermore, we analyze changes in landscape metrics to examine possible effects of changes in the habitat and on rupestrian grasslands' biodiversity.

Materials and methods

Identification of priority regions

To delineate priority regions for this study and conservation of rupestrian grasslands we used spatially-explicit data points of the location of rupestrian grasslands deemed as conservation priority by experts who participated in the 1st Workshop on Biodiversity, Conservation, Use and Public Policy in Rupestrian Grasslands, in Belo Horizonte (Brazil), in October 2011, focusing on the core area of the Espinhaço mountain range and the Canastra mountains (GWF, unpublished data). A total of 300 occurrence points for rupestrian grasslands were generated covering the entire "core area" of the Espinhaço mountain range and the Canastra mountains. These two regions were chosen because of their strong representation of this ecosystem (see Fernandes 2016a). Additional coordinates were kindly provided by M Callisto, AA Conceição, and L Echternacht for localities in the northern part of the Espinhaço mountain range, the Canastra mountains and other isolated mountains in Goiás, Mato Grosso and Roraima states. In total, we registered 490 points of occurrence of rupestrian grasslands in Brazil, which resulted from an extensive discussion during the abovementioned workshop between experienced researchers about the distribution of the ecosystem.

Environmental data

Bioclimatic variables are commonly used predictors of the impacts of climate change on biodiversity (Schrag et al. 2008). We assumed that such variables would satisfactorily determine the distribution of rupestrian grasslands in a historical context, given the strong associations of climate with the biotic environment (Carnaval and Moritz 2008; Garcia et al. 2016). Bioclimatic and elevation variables, used in conjunction, were downloaded from the WorldClim platform at a spatial resolution of 0.0083° (~1 km^2) (see Hijmans et al. 2005 for further details) for the period of 1950–1990. Aspect and slope data, derived from elevation, were generated using the Spatial Analyst Toolbox within the software ArcMap® (ESRI, California). Finally, we created a binary variable corresponding to areas where the predominant lithology is associated with rupestrian grasslands, such as quartzite formations, sandstone, silts, phyllites, meta-conglomerates, and iron ores (Schaefer et al. 2016; see also Le Stradic et al. 2014; Barbosa and Fernandes 2016). We assumed that this edaphic factor will remain largely unchanged under future climate scenarios. The shapefiles relating to the geological classifications for Brazil (scale 1:10,00,000) were downloaded from the Brazilian Geological Survey GEOSGB (http://geosgb.cprm.gov.br/) and processed through the software ArcMap® (ESRI, California) at a spatial resolution of 0.0083° (~1 km^2).

Bioclimatic variables for year 2050 (averaged from 2041 to 2060) and year 2070 (averaged from 2061 to 2080) were also downloaded from WorldClim and followed the same spatial resolution of 0.0083° (Hijmans et al. 2005). We used data from five different climate models (Table 1), to reduce the uncertainty of predictions resulting from a single global circulation model (GCM), in two concentration pathways: RCP 4.5 and RCP 8.5 (e.g., Khanum et al. 2013). Of these scenarios, the most pessimistic is the RCP 8.5, which assumes that global annual greenhouse gases continue to rise throughout the 21st century, and the more optimistic is RPC 4.5, which assumes that global annual greenhouse gas emissions peak around 2040 with emissions declining substantially thereafter (IPCC 2014). Other scenarios (e.g., RCP 2.6 and the RCP 6) were tested but not chosen, due to unrealistic predictions (a decrease in emissions at the end of this decade), and similar results of RCP 8.5, respectively. All models were used in combination, and the main result was the mean output.

All variables were clipped to cover the Brazilian territory, encompassing the entire known distribution of rupestrian grasslands, including small relict areas. We built a Pearson correlation matrix to detect the presence of multicollinearity between variables, and among those highly correlated variables (i.e., those with $r \geq 0.8$), we opted to keep in the model those variables with higher biological relevance. Following this protocol, out of 19 bioclimatic variables initially selected, only eight were retained in the final model, in conjunction with the variables "elevation", "aspect", "slope" and "lithology" (Table S3).

Predictive modeling

Distribution models were built with the maximum entropy approach (MaxEnt) (Phillips et al. 2006; Elith et al. 2011). This algorithm can perform effective analysis even with small samples using only presence data (Hernandez et al. 2006). The algorithm was implemented by the software MaxEnt, version 3.3.3 (Computer Sciences Department—Princeton University 2004), which was used for the generation of a logistic model for the distribution of rupestrian grasslands under baseline climate conditions for the period of 1950–1990 (e.g., Phillips et al. 2006). This model was then projected to the future scenarios.

We used tenfold cross-validation for testing model performance (10 replicates) and averaged the results. We also used the jackknife procedure and permutation importance to estimate the relative influence of different predictor variables. The area under the ROC (receiver operating characteristic) curve (AUC) was used to evaluate model performance (Swets 1988). In addition, a threshold was selected which enabled us to obtain information about future suitable areas, which represent potential priority areas for the conservation of rupestrian grasslands. The chosen threshold was the "10 percentile training presence logistic threshold", which shows the most realistic result and converts the

Table 1 Climate models used in the predictions of the rupestrian grassland potential distribution models

Model	Name
BCC-CSM1.1	Beijing climate center-climate system model 1.1
CCSM4	Community climate system model 4.0
GISS-E2-R	NASA Goddard Institute for Space Studies modelE2
HadGEM2AO	Hadley centre global environmental model version 2 (Atmosphere–Ocean)
MIROC5	Model for interdisciplinary research on climate version 5

probability distribution derived from the model into a binary map of presence/absence (Liu et al. 2005). To avoid erroneous predictions of suitable habitat under future climate scenarios for 2050 we used the "fade-by-clamping" option in MaxEnt, which removes heavily-clamped pixels from the final predictions (e.g., Khanum et al. 2013).

Landscape metrics and land-use threats/protection

We conducted three analyses on how changes in environmental suitability and land-use will affect the biodiversity of rupestrian grasslands in current and future scenarios, given an increasingly complex set of assumptions. Firstly, we assessed how changes in environmental suitability will affect landscape metrics, if all suitable areas are covered by native habitat (overall landscape metrics). The second analysis consisted of overlapping the current land-use with present and future areas of suitability under different scenarios, if land-use will not change (overall land-use threats and protection). The third analysis deals with the effect of mining only, overlapping areas of environmental suitability with areas directly and indirectly affected by mining in the current scenario and in a mining expansion scenario.

The analysis assessed changes in area and connectivity for rupestrian grasslands' species in current and future scenarios using Fragstats (McGarigal et al. 2012). For this analysis, we assumed that all suitable areas are covered by native habitats. We assessed the following landscape metrics: total habitat area, number of patches, mean patch area, mean nearest neighbor (MNN), and proximity indexes. MNN is the average edge-to-edge Euclidean distance between a focal patch and the next nearest patch. Proximity is the association between area and inter-patch connectivity. Increasing proximity indices means that the landscape is more structurally connected, while low values indicate a decrease in connectivity. We used a 5000 m threshold as a search radius, assuming this is a reasonable distance for the dispersion of plants and vertebrates in this time scale.

To measure how much area is being (and will be) affected by intensive use, as well as how much area is (and will be) within protected areas, we overlapped current land-use with present and future areas of suitability. This analysis assumed that land-use would not change with time. Silviculture, intensive agriculture (soybeans, sugar cane, corn, cotton, rice, wheat, bean, coffee, orange, tobacco, cocoa, banana, and cassava) and urban areas for the entire Brazilian territory at a 30-m resolution were acquired from the Centro de Sensoriamento Remoto—CSR UFMG and kindly made available by Britaldo Soares-Filho. Maps of current mining activities were acquired from the Departamento Nacional da Produção Mineral (DNPM) website (http://sigmine.dnpm.gov.br/sad69/UF.zip, April 2013) and comprised areas under different phases of activity development: exploration, licensing, concession, and exploitation.

We overlapped the current mining maps with predicted areas of suitability in the present and future. Assuming that indirect impacts of mining reach 5 km (Durán et al. 2013), we built buffers around mines and calculated the proportion of the areas of suitability affected both directly and indirectly by mining. Additionally, we created mining expansion (ME) scenarios, in which all current areas under licensing or requesting mining authorization were considered; which were also overlapped with future areas of suitability. The ME scenario is the best approximation of where future mines will be placed, although this is a rather conservative approximation, as many mines could be implemented outside these areas. Finally, our models were built considering the following 12 scenarios: (1 and 2) current (considering current suitability and mining distribution), (3 and 4) 2050 RCP4.5 (climatic optimistic and current mine distribution), (5 and 6) 2050 RCP4.5 ME (climatic optimistic and mining expansion), (7 and 8) 2050 RCP8.5 (climatic pessimistic and current mining distribution), (9 and 10) 2070 RCP4.5 (climatic optimistic and current mining distribution) and (11 and 12) 2070 RCP8.5 ME (climatic pessimistic and mining expansion scenario).

Results

Predictive modeling

The current area of environmental suitability for rupestrian grasslands in Brazil is approximately 83,000 km^2 (South America Albers Equal Area Conic projection, "10 percentile training presence logistic threshold"), surpassing the area previously estimated by Fernandes et al. (2014) and Silveira et al. (2016). In our models, suitability was largely driven by topography and climate. Altitude, temperature seasonality, and annual precipitation were deemed the most important variables in the model (Table S3). The model showed a satisfactory performance with an AUC value of 0.972 (±0.003, SD), which indicates a high accuracy.

The current distribution of rupestrian grasslands is largely affected by topography/lithology and climate and, as such, one could intuitively derive the effects climate change might have on its range and its conservation. In fact, under a more optimistic scenario (RCP4.5), we estimated a total loss of ca. 57,300 km^2 (69%) of suitable areas for rupestrian grasslands by 2050 and a loss of ca. 60,000 km^2 (72%) of suitable area by 2070. This loss was concentrated in the regions of Chapada Diamantina, northeastern parts of the Espinhaço and in the south of Minas Gerais and Goiás states (Fig. 3a, c). Additionally, all the isolated mountains in northeastern and northern parts of Brazil will lose suitability for rupestrian grasslands.

Under the more pessimistic scenario (RCP8.5), the loss of suitable areas would reach ca. 60,500 km^2 (73%) by around 2050, and ca. 68,380 km^2 (82%) in 2070, with areas only remaining in the southern part of the Espinhaço and fragmented areas in Chapada Diamantina, in the Iron Quadrangle, and in Serra da Canastra (Fig. 3b, d). More stable regions, likely to remain climatically suitable until the end of this century are the mountains of southern Minas Gerais, Ouro Preto, Caraça, Serra do Cipó, Canastra, part of the Diamantina plateau and fragments in the northern part of the Espinhaço range (Fig. 3). Currently, less than 10% of the distribution of this ecosystem is protected (ca. 7720 km^2), which is below the 17% target according to the Convention on Biological Diversity (CBD; https://www.cbd.int/sp/targets/). Our results show this scenario can worsen in the near future due to the loss of suitable areas in the face of climate change. Loss of suitable areas for rupestrian grasslands could effectively shrink these conservation units by ca. 40% of the current size in 2050, reaching up to 55% in 2070 (Table 2).

Landscape metrics and land-use threats/protection

Even assuming that rupestrian grasslands will cover all suitable areas predicted by the model, the average patch size will decrease by more than half in 2070. More disturbingly, patches would be getting smaller and their number will decrease up to four-fold in the worst scenario. Due to habitat fragmentation, patches will be more separated as shown by a slight increase in the mean nearest neighbor distance. Also, connectivity indices that consider patch area, such as proximity, will be halved in the 2070 pessimistic scenario (Fig. 4).

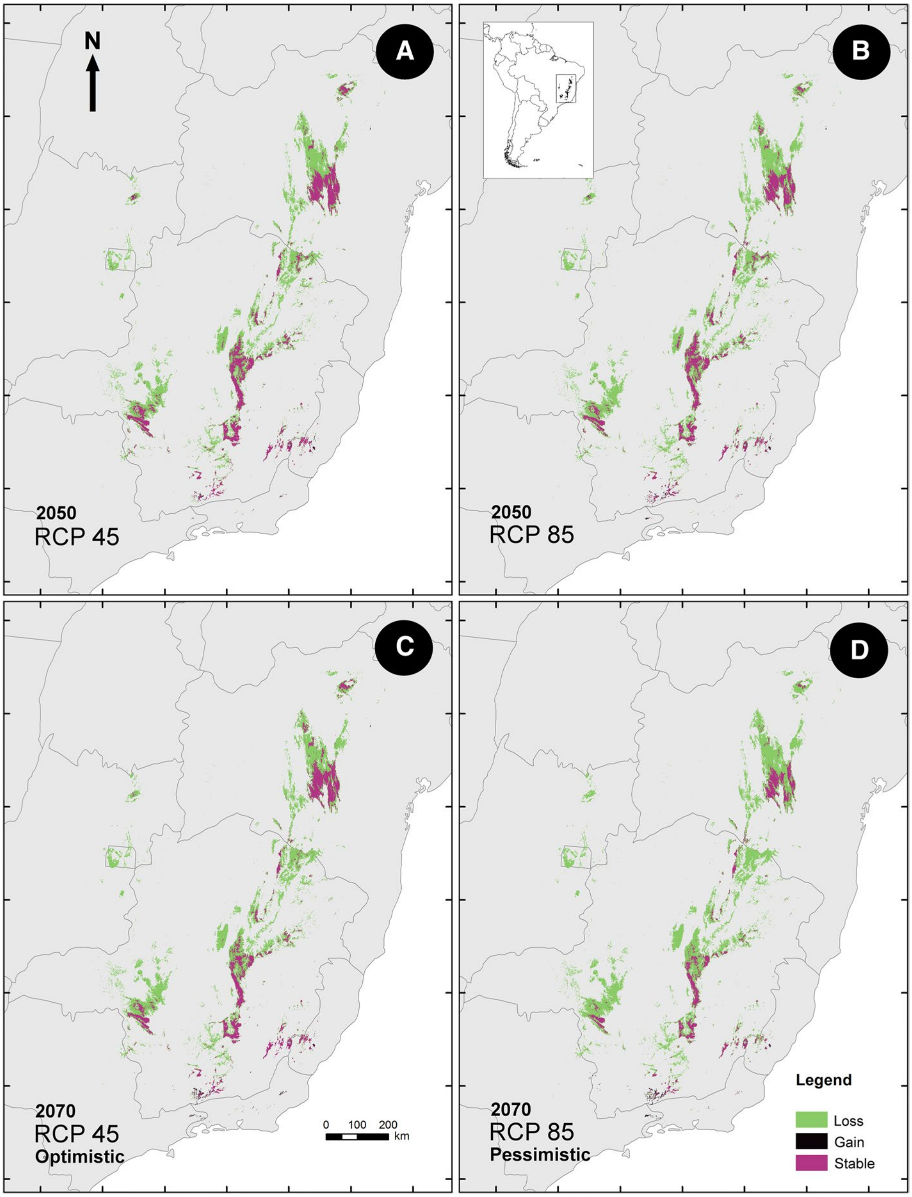

Fig. 3 Projection of environmental suitability for rupestrian grasslands centered around 2050 in an optimistic RCP 4.5 (**a**) and in a more pessimistic RCP 8.5 scenario (**b**). Projection of environmental suitability for rupestrian grasslands centered around 2070 in an optimistic RCP 4.5 (**c**) and in a more pessimistic RCP 8.5 scenario (**d**)

We found that environmentally suitable areas for rupestrian grasslands will decrease from 8.3 million ha to less than 2.6 million in any of the future scenarios (Fig. 5a). Assuming that current land-uses will be adhered to, the area under intensive use (i.e., agriculture, silviculture, urban and mining) will decrease from the currently 1.2 million hectares to a

Table 2 Loss of protected areas in rupestrian grasslands for the decades centered around 2050 and 2070, under two representative pathways: RCP 4.5 and RCP 8.5

Year	Representative pathways	Loss of protected areas (%)	Loss of protected areas (km^2)
2050	RCP 4.5	39.19	3025.09
	RCP 8.5	40.62	3135.43
2070	RCP 4.5	45.10	3481.10
	RCP 8.5	54.84	4232.98

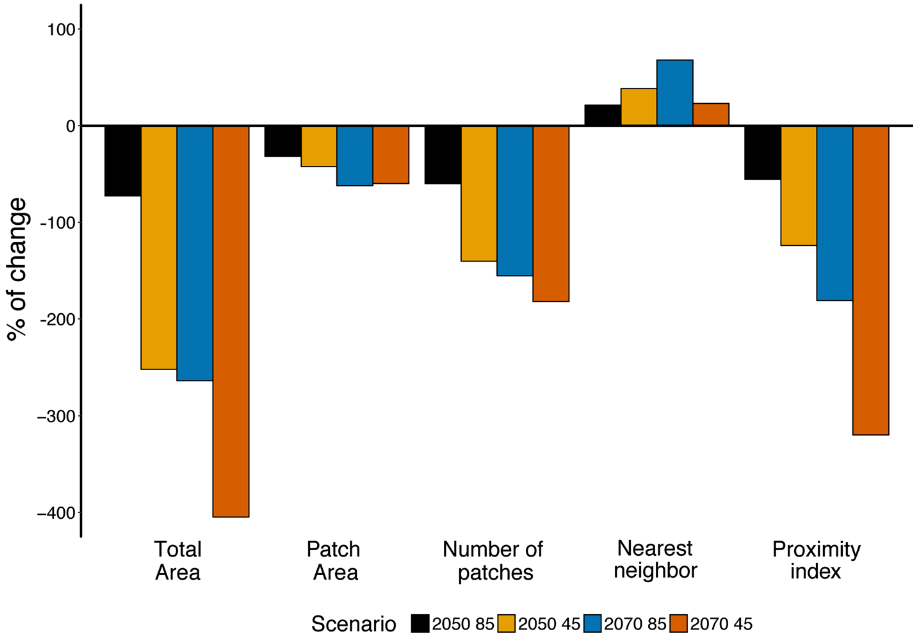

Fig. 4 Landscape metric changes from the current situation to future scenarios according to different landscape indices. It was assumed that all suitable areas are covered by natural habitats

number between 0.197 and 0.076 million ha in the future scenarios. This means that, as the total area of the rupestrian grasslands shrink, many areas currently under mining and agriculture pressure will not be adequate for the biota of rupestrian grasslands in terms of bioclimatic variables explaining the decline in total impacted area. Nevertheless, these estimates assume no changes in land-use, which is clearly unrealistic. Additionally, the proportion of the habitat area under intensive pressures is maintained in the future scenarios, especially if indirect impacts of mining are considered and in the mining expansion scenarios. Therefore, the relative impact of intensive managements remains similar if land-use does not change, and probably increase if agricultural and silviculture practices expand.

If the current network of protected areas is maintained, 1.2 million hectares (0.83 million hectares of strictly protected and 0.42 million hectares of sustainable uses reserves) will fall to a number between 0.71 and 0.53 million hectares in the future scenarios. Currently, 0.29 million hectares of rupestrian grasslands are under direct effect of mining, which is about 3.5% of the total area of suitability (Fig. 5b). If both indirectly and directly

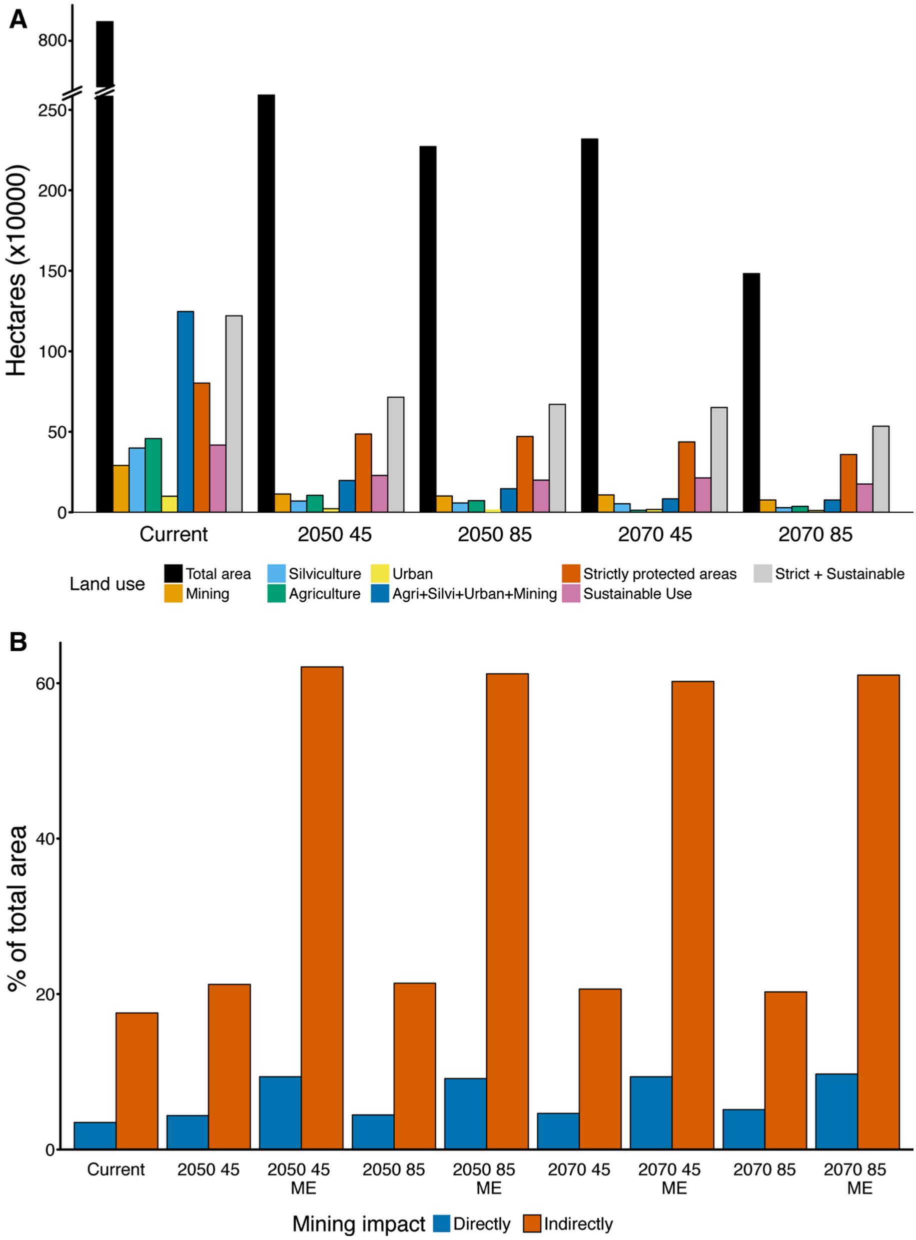

Fig. 5 Area under different land-uses in the current and future scenarios, assuming that land-use is kept in current conditions (**a**). Proportion of suitability areas for rupestrian grasslands indirectly and directly affected by mining and according to two mining scenarios (current, and mining expansion - ME) in different future scenarios (**b**)

affected areas are considered, this value rises to about 1.5 million ha, or 17.57% of the ecosystem's distribution. Assuming all mines that are currently under licensing, or in any stage of authorization will become effective, the proportional area affected (directly and indirectly) may be more than 60% in the future scenarios. Because we expect that mines will increase beyond areas that are currently under licensing, the actual mined area can be even larger than the scenario of mining expansion predicts.

Discussion

While there has been no significant expansion of the distribution of rupestrian grasslands since at least the Last Glacial Maximum (ca. 20,000 years B.P.) (Barbosa and Fernandes 2016), future scenario predictions are catastrophic for this ecosystem. All models applied here showed extremely negative results in terms of maintenance of suitable areas for conservation of rupestrian grasslands under climate change, reaching losses of up to 82% within the next 50 years. We also showed that a small proportion of protected areas become less effective due to the loss of suitability, land-use changes, mining and lack of adequate knowledge and policing for its conservation and management (e.g., Fernandes 2016b). Moreover, more than 50 million people that depend on ecosystem services provided by rupestrian grasslands (Neves et al. 2016) could be directly or indirectly impacted, extending the pressure on an already overexploited land.

Although 10 strictly protected areas were created in rupestrian grasslands in the last decade, safeguarding about 116,000 ha (Silva et al. 2008), unique elements of biodiversity are likely to be under-represented due to species turnover and high endemism (Fernandes 2016b; Monteiro et al. 2018). Although the mining industry has acquired several properties in the Espinhaço range to offset the impacts of mining, most of them have not been officially transformed into protected areas yet and, therefore, not included in the analyses performed to date (GWF, unpub. data). Although in this region offsetting efforts has rarely reduced vegetation loss and are themselves often threatened by future mining (see Sonter et al. 2014b), we ought to build spaces and opportunities to create a pact that will lead to a more rational use and conservation of the rupestrian grasslands.

The case of Brazilian rupestrian grasslands calls for profound scientific, conservation and political consideration due to their unparalleled biodiversity and levels of endemism, plus their strategic importance as a source of goods, including water, ornamental species, and scenic beauty for sustainable tourism, especially for the densely populated southeastern Brazil (Resende and Fernandes 2013; Resende et al. 2017). Mountain environments in the Cerrado have until recently been relatively free from huge extensive cattle farming and habitat-aggressive plantations, such as soybean and sugar cane (Gibbs et al. 2015). However, this situation is not likely to continue, as indicated by uncontrolled habitat conversion and the disturbances highlighted here. The worsening fate of rupestrian grasslands could scale-up both spatially and temporally if we consider the fast pace of biological invasions (Barbosa et al. 2010; Fernandes et al. 2015), mining activities (Fernandes et al. 2014; Sonter et al. 2014a) and afforestation projects (Veldman et al. 2015; Fernandes et al. 2016b). The synergy of these strong drivers would result in major land-use change leading to strong impacts from which the low-resilience rupestrian grasslands might not recover, perhaps leading to novel and much more simplified ecosystems both botanically (Fernandes et al. 2014) and zoologically (Dirzo et al. 2014) that are deficient in the provision of ecosystem services.

Currently, ca. 15% of rupestrian grasslands are subjected to intensive anthropogenic impact (areas directly affected by mining, silviculture, urbanization and intensive agriculture). Considering the indirect impacts of mining reach 5 km beyond the mines themselves (a very conservative estimate, Durán et al. 2013), as much as 18% of the ecosystem is currently under the influence of mining alone (Fig. 5). The projected expansion of the mining sector in rupestrian grasslands would lead to an unprecedented cascade of impacts on the ecosystem (Fernandes et al. 2014; Fernandes and Ribeiro 2017; Pena et al. 2017). If the expansion of mining comes associated with climate change, the direct and indirect effects of mining would reach about 60% of the total future distribution of rupestrian grasslands under the pessimistic and optimistic 2045 and 2070 climatic scenarios (Fig. 3). This happens since the distribution of future mines largely overlaps with suitable areas of rupestrian grasslands potential distribution.

One anthropogenic threat that disrupts the rupestrian grassland dynamics, not yet mentioned or included in our models and predictions, is the occurrence of anthropogenic fires. Although rupestrian grassland is a fire-prone vegetation, adapted to natural fires (Warming 1892; Silveira et al. 2016; Morellato and Silveira 2018), the time, intensity and frequency of human-induced fires impose additional stresses to plants, with unforeseen effects on the entire ecosystem (e.g, Figueira et al. 2016; see also Bond and Keeley 2005). Rupestrian grasslands are moisture-dependent, fire regime ecosystems, with the ignition influenced mostly by the length of the dry season and the rainfall distribution along the season (Alvarado et al. 2017). The effects of changes in fire regime, caused by anthropogenic activities or indirectly through climate change, are still unknown for this ecosystem and concur with mining and other threats. Monitoring of the vegetation recovering post-fire is needed (Figueira et al. 2016; Alberton et al. 2017) to evaluate the ecosystem's potential resilience as well as whether the effects of anthropogenic fire regime are positive or negative in the areas disturbed by mining and other activities, integrating the management plan of conservation units.

Concluding remarks and future perspectives

Proactive and long-lasting actions are urgently needed to preserve this ecosystem and its irreplaceable ecosystem services for future generations. In the next few decades we will not just face loss of biodiversity and ecosystems services and processes, but we also risk losing an important cultural heritage (Neves et al. 2016; Fernandes and Ribeiro 2017). A first step towards effective conservation of rupestrian grasslands is the translation, to all sectors of society, of the knowledge and importance of this ecosystem and the magnitude of the loss due to its conversion and misuse. For instance, the consequences of the loss of environmental services and of the overexploitation of natural resources leading to deterioration of human wellbeing is an aspect that needs to become appreciated (see Biénabe and Hearne 2006; Resende et al. 2017). Conservation actions, however, are challenged by a number of basic limitations, including that the vast majority of the conservation units in the region lack planning, personnel, and the engagement of communities. The problem becomes even more complex and challenging as conservation plans developed for forested areas, cannot be transferred by governmental institutions to these grassland ecosystems, and instead need to be specifically developed for non-forest landscapes. This is an aspect that needs to be assimilated by local governmental institutions if they are to administer one of the most diverse and neglected ecosystems of Brazil (Fernandes 2016b). This comes at a time when increasing land-use change is accelerating. Last, but not least, while the Brazilian panel of climate change (Ambrizzi and Araujo 2014) predicts an increase of ca. 5 °C in temperature and a decrease of 35–45% in rainfall by the end of this century in central Brazil, no specific information has been provided for rupestrian grasslands or the Espinhaço mountain range. The above scenario represents an enormous problem from a conservation perspective, firstly because this mountain ecosystem holds unique elements of Brazilian biodiversity and ca. 50% of the species of the Cerrado (i.e., the most diverse savanna of the world and the second largest biome in South America: Fernandes 2016c), and secondly because mountaintops in this region hold the headwaters of major rivers and watersheds (river basins occupy an area of 1.21 million km^2) that provide water to 50 million people and to mining, industry, agriculture, aquaculture, fishing, and transportation in southeastern and northeastern Brazil. Clearly, rupestrian grasslands represent a critical conservation agenda.

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