RESEARCH PAPER

Outstanding plant endemism levels strongly support the recognition of *campo rupestre* provinces in mountaintops of eastern South America

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Abstract

Aim: The Brazilian *campo rupestre* is a vegetation associated to ancient mountaintops in eastern South America, spread mainly over disjunct areas of the Espinhaço Range and the Chapada dos Veadeiros. These areas hold outstanding levels of plant diversity and endemism, but despite their uniqueness they have been neglected in recent bioregionalizations for the Neotropical region. Given their particular levels of species richness and endemism, we here test the recognition of these as distinct bioregions within the Chacoan dominion.

Location: Mountaintops of eastern South America.

Methods: We listed 1,748 angiosperm species endemic to the *campo rupestre* of the Espinhaço Range and Chapada dos Veadeiros regions, based on the data gathered from the Brazilian Flora 2020 Project. We extracted all occurrence information available from GBIF (the Global Biodiversity Information Facility) for such list and also for a polygon gathering all the study area, including information from adjacent vegetations. Data went through standard cleaning procedures and a network clustering analysis was performed to delimitate the boundaries of the new bioregions.

Results: Our data strongly support the recognition of two distinct bioregions along the Espinhaço Range, but none in the Chapada dos Veadeiros. Given their high levels of endemism and singularity within the Chacoan dominion, we formalize two provinces associated to *campo rupestre* in the Espinhaço Range, naming them as "Chapada Diamantina" and "Southern Espinhaço" provinces. Within the latter province, three districts are also recognized, based on this and previous studies: "Diamantina Plateau", "Grão-Mogol" and "Iron Quadrangle" districts.

Main conclusions: The formalization of new and previously described bioregions highlights the *campo rupestre* as a vegetation harbouring outstanding levels of species richness and endemism in South America, contributing to a better understanding of biogeographical patterns in the Neotropics. Also, as we follow the International Code of Area Nomenclature as a device to standardize recognition of bioregions, this shall facilitate further biogeographical and conservation studies in these areas. Further assessments with new and revisited data are needed to enable minor scale bioregionalization within the Chacoan dominion.

1 | INTRODUCTION

1.1 | Humboldt's legacy and the concept of bioregion

Just as the definition of species, in all its complexity, facilitates our comprehension on the boundaries of natural entities, the definition of biogeographical regions (henceforward bioregions) facilitates our understanding on the distribution of biotas in space (Morrone, 2018). They are useful in improving practicality of conservation measures (Gustafsson et al., 2014), in studies of lineage evolution and ecology, or in simply facilitating communication among scientists (Morrone, 2017).

Humboldt was a pioneer in establishing the foundation of physical and plant geography sciences. His ideas formed the basis of subsequent recognition of major bioregions, proposed by prominent authors such as J.F. Schouw, P. Sclater, A.R. Wallace and A.P. De Candolle during the 19th century. Ever since, continuous efforts to accurately define bioregions have been made, but it is impressive to see how most of the classical bioregions stand the same despite the development of new methodological approaches (e.g., Holt et al., 2013; Morrone, 2015a). This highlights how Humboldt and his contemporaries' contributions still reflect on current works.

Notwithstanding, traditional criteria used in the circumscription of bioregions often were not precise neither fully explicit (Cabrera & Willink, 1973; Müller, 1973; Rivas-Martínez & Navarro, 1994; Wallace, 1876). New analytical frameworks, objective criteria and larger databases of different taxa are now required for a strongly supported bioregionalization (Kreft & Jetz, 2010; Mackey, Berry, & Brown, 2008; Morrone, 2018). In this sense, biogeographers have advanced greatly in knowledge by discovering new bioregions (Droissart et al., 2018; Ebach, 2015) or by testing and revisiting previous ones (Holt et al., 2013; Morrone, 2014).

This culminated in the establishment of an International Code of Area Nomenclature, henceforth ICAN (Ebach, Morrone, Parenti, & Viloria, 2008). As the definition of a bioregion sometimes is not consensual and must be revisited (Noguera-Urbano, 2016), a standard code such as ICAN can provide objective rules and criteria on classifying bioregions hierarchically (Morrone, 2018).

1.2 | Brazilian ancient mountains and the *campo rupestre* vegetation

Despite Humboldt's interest on the exceptionally rich biota of the Andes, another montane vegetation on the opposite side of South America also requires closer attention from biogeographers, given its particular levels of species richness and endemism: the *campo rupestre*, a shrubby-herbaceous vegetation associated to rock outcrops

and shallow, sandy soils on ancient mountaintops. This vegetation occurs mainly in two disjunct areas in Central and Eastern Brazil: the Espinhaço Range and the Chapada dos Veadeiros (Alves, Silva, Oliveira, & Medeiros, 2014; Vasconcelos, 2011) (Figure 1).

The Espinhaço Range is a major mountainous extension geomorphologically divided on the southern (Minas Gerais state) and northern (Bahia state) portions (Gontijo, 2008). In terms of vegetation (i.e., phytophysiognomy or ecoregions), the Espinhaço Range is an enclave between the Atlantic Forest, Cerrado and Caatinga (Conceição et al., 2016). On the other hand, the Chapada dos Veadeiros is a highland area nested within the Cerrado ecoregion as a part of a plateau located in the states of Goiás and Tocantins, including the highest altitudes of central Brazil (Lenza, Pinto, Pinto, Maracahipes, & Bruziguessi, 2011).

Conversely, in terms of biota (i.e., faunistic/floristic endemism or bioregions), the *campo rupestre* has long been recognized as areas harbouring outstanding levels of species richness and endemism (Alves et al., 2014; Bitencourt & Rapini, 2013; Echternacht, Trovó, Oliveira, & Pirani, 2011; Giulietti, Pirani, & Harley, 1997; Harley, 1988; Joly, 1970; Moro et al., 2015; Neves et al., 2018; Nogueira, Ribeiro, Costa, & Colli, 2011; Vasconcelos & D'Angelo-Neto, 2007; Vasconcelos & Rodrigues, 2010). It is estimated that c. 5,000 plant species are native to these areas, which means that this vegetation includes approximately 15% of all Brazilian native plant species in an area smaller than 1% of the country's territory (based on the Brazilian Flora 2020 Project database, henceforward "BFG").

Despite the increasing understanding about the *campo rupestre* biota in the last three decades, this remarkable vegetation has been neglected in recent bioregionalization proposals in the Neotropics – for example, they are missing in Morrone's (2014) regionalization system. Concurrently, there is no consensus among researchers on how *campo rupestre* areas should be divided and classified. Prance (1994), for instance, considers all of the disjunct patches of *campo rupestre* vegetation scattered along the Central Brazilian Plateau as a single floristic unit, which he designated a "floristic archipelago". Other authors, however, suggest two or more floristic units (which could be interpreted as different bioregions), based on analyses from datasets of particular groups (e.g., Harley, 1988; Echternacht et al., 2011). More than one bioregion was also sometimes recovered considering animal taxa, such as birds or reptiles (e.g., Vasconcelos, Lopes, Machado, & Rodrigues, 2008; Nogueira et al., 2011).

Hence, formally testing congruent *campo rupestre* bioregions considering the entire vegetation and in light of the current paradigm of bioregionalization is still a necessary task. In this study, we test (a) if areas of *campo rupestre* vegetation can be distinguished from the surrounding bioregions of the Chacoan dominion when they are subjected to a broad-scale analysis; and (b) how many

portions of *campo rupestre* vegetation can be recovered as singular bioregions, encompassing particular sets of endemic species and taxonomical composition. New bioregions are named considering the ICAN rules and results are discussed in the evolutionary context of these areas.

2 | MATERIALS AND METHODS

2.1 | Definition of *campo rupestre* vegetation

The expression "*campo rupestre*" was first coined by Magalhães (1966) and the precise definition has been a matter of debate since then. Vasconcelos (2011) and Alves et al. (2014) revisited this debate and defined *campo rupestre* as "mountaintop vegetations of areas above 900 m of altitude, occupying stretches of lithosols associated to outcrops of quartzite and sandstone". This definition has been more or less followed by subsequent authors (e.g., Longhi-Wagner, Welker, & Waechter, 2012; Conceição et al., 2016; Silveira et al., 2016; Pontara et al., 2018), including the BFG. We also follow it here.

Currently, there is a general agreement that *campo rupestre* are geologically and floristically associated to the Cerrado and Caatinga vegetations (Moro et al., 2015; Neves et al., 2018; Zappi, Moro, Meagher, & Lughadha, 2017). However, the *campo rupestre* was previously understood by several authors as a major floristic province distinct from the Cerrado and Caatinga flora due to its particular phytophysiognomy and set of endemic species (e.g., Eiten, 1978; Harley, 1988; Prance, 1994; Zappi et al., 2017). This is a point of view we test here.
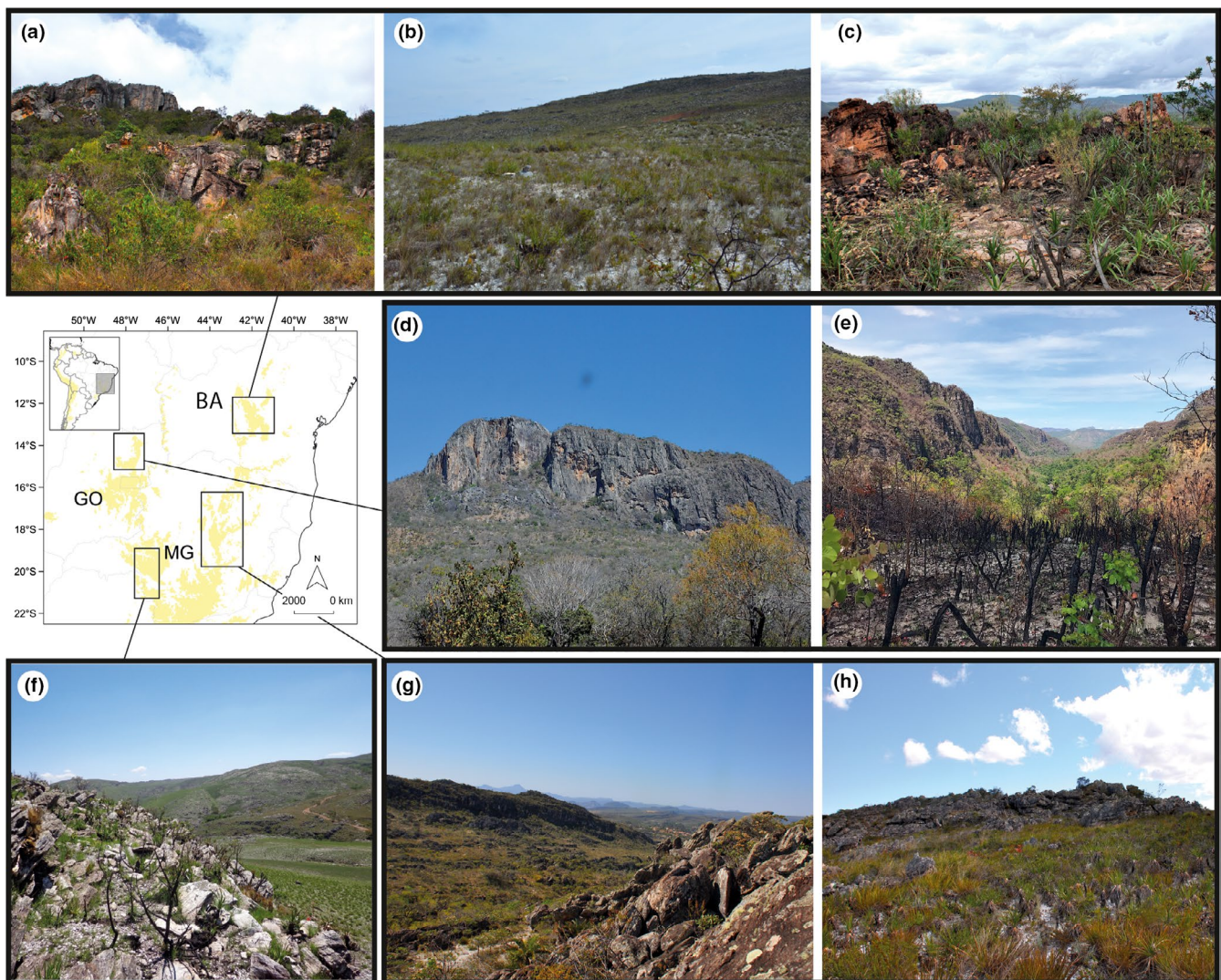
FIGURE 1 Examples of *campo rupestre* landscapes in three distinct areas in Central and Eastern Brazil, showing characteristic rocky outcrops, quartzite and sandstone soils, events of fire and typical shrubby-herbaceous vegetation. (a) Mucugê (12°59′S 41°22′W, 1,000 m altitude), (b) Rio de Contas (13°35′S 41°48′W, 1,100 m altitude) and (c) Andaraí (12°43′S 41°19′, 900 m altitude), all in Bahia state (BA – Northern portion of the Espinhaço Range). (d) and (e) Alto Paraíso de Goiás (14°10″S 47°50″W, 1,000 m altitude) in the state of Goiás (GO – note vegetation recovering from fire event in "e"; Chapada dos Veadeiros region). (f) Serra da Canastra (20°20″S 46°38′W, 1,000 m altitude) (g) Diamantina (18°14′S 43°35′W, 1,200 m altitude) and (h) Serra do Cipó (19°15′S 43°33′W, 1,300 m altitude), all in Minas Gerais state (MG – Southern portion of the Espinhaço Range). Photos by T.N.C. Vasconcelos except (f), which is by L.J. Sauthier [Colour figure can be viewed at wileyonlinelibrary.com]

2.2 | Datasets

In order to test if the *campo rupestre* areas in the Espinhaço Range and Chapada dos Veadeiros can be recognized as singular bioregions, we ran two similar analyses with two different datasets. First, we compiled a working list of *campo rupestre* angiosperm species only (dataset one), using data retrieved from the BFG (BFG, 2018b) as a main source for data assessment. We must stress that the data maintained by the BFG (<http://floradobrasil.jbrj.gov.br>) are sound, carefully checked by hundreds of taxonomists currently studying particular families or genera (BFG, 2015; 2018a). As the BFG is continuously updated, information regarding particular taxa may still change in the near future.

This working list was compiled by filtering all species assigned as "endemic to *campo rupestre*" in this database. From that, we considered only species recorded to the following Brazilian federal units (states): Bahia and Minas Gerais (in which the Espinhaço Range lies), and Goiás, Distrito Federal and Tocantins (in which the Chapada dos Veadeiros lies). This filtering procedure provided us an all-encompassing taxonomic-validated list of all reported angiosperms endemic to the two wider areas of *campo rupestre* in the Brazilian Shield, which represent all the *campo rupestre sensu* Alves et al. (2014).

A second working list (dataset two) was compiled by listing all angiosperm species occurring in a polygon drawn between 9°–20°S and 40°–51°W – corresponding to the minimum and maximum latitudinal/longitudinal points of the study area. This second dataset was compiled to include both *campo rupestre* and adjacent vegetations, in order to have a second set of evidence that is unbiased towards endemism in *campo rupestre*.

For both datasets, we extracted all information regarding distribution records for species from Global Biodiversity Information Facility (GBIF, <http://www.gbif.org>) using the "dismo" package in R Environment (Hijmans, Philips, Leathwick, & Elith, 2017; R Development Core Team, 2018). We included only presence records with valid and complete coordinates, and only those which can be associated to herbarium vouchers.

We made standard data cleaning procedures to minimize as far as possible any inaccurate or uncertain records. This included the removal of invalid coordinates (i.e., sea points, inverted or poorly defined coordinates, coordinates assigned to biodiversity institutions or country/state centroids), duplicated and outlier records that did not correspond to the overall distribution pattern of the species as informed by the data retrieved from the BFG. Data cleaning procedures and maps were performed in the "CoordinateCleaner" package in R (Zizka et al., 2019) and using the QGIS software and its tools (<http://www.qgis.org>).

2.3 | Floristic profiles and life forms

To visualize the most diverse plant groups and life forms in each portion of *campo rupestre*, we used the "state of occurrence" as a proxy to discriminate species occurring in Chapada dos Veadeiros (filtering all species occurring in the states of Distrito Federal, Goiás and Tocantins), northern and southern portions of the Espinhaço Range (filtering all species occurring in the states of Bahia and Minas Gerais, respectively). "State of occurrence" was used as a proxy to discriminate these three disjunct areas because this information is already provided by the BFG. Life forms were also classified according to the definition of the BFG, that is, as either shrub, subshrub, tree, bamboo, dracaenoid, herb, liana/scandent/vine, palm tree or succulent.

2.4 | Recognizing and formalizing bioregions

To recognize new bioregions of *campo rupestre*, we used the "Infomap Bioregions", a method first described by Vilhena and Antonelli (2015). This algorithm has been shown efficient, fast and accessible, and it has been widely applied to define other bioregions (e.g., Zizka, Steege, Pessoa, & Antonelli, 2018; Droissart et al., 2018). As this method is flexible and chooses the most indicative species given a set of records, it can deal with big-data subject to georeferencing errors, such as the GBIF database (Beck, Böller, Erhardt, & Schwanghart, 2014; Maldonado et al., 2015; Yesson et al., 2007).

We performed these analyses in the two distinct datasets described above (section "2.2. Datasets") using five different sets of parameters, testing from a range of highly laxer to highly conservative ones. We also tested different minimum and maximum cell capacities – the minimum/maximum number of records in a grid cell to include in the map analysis – from 10 to 50, 100, 200 and then 300.

We also examined different cluster costs – the tune of the clustering algorithm to search less or more clusters or, in other words, bioregions – from 1.0 (pre-set default) to 1.2, 1.4, 1.6, 1.8 and then 2.0. We chose to test higher values of cluster costs because *campo rupestre* areas are relatively small but with high density of microendemic species, and small values of cluster cost would over-split the areas of interest.

For all cluster analysis, we performed 10 trials with minimum and maximum cell size of 0.5°. The output included a summary informing the ten of the "most common", that is, species with more records, and the ten of the "most indicative" species for each bioregion. An "indicative species" is as a taxon whose records are more frequent within a particular bioregion delimitated than the overall dataset (Edler, Guedes, Zizka, Rosvall, & Antonelli, 2016).

Based on the ten most indicative species informed by the clustering analysis, we returned to their original distribution to delimit the areas of the new bioregions (as recommended by Morrone, 2018) by making a minimum convex polygon. We delimited the bioregions also based on Morrone's (2014) boundaries for the regionalization in the Neotropics, which is the most used and detailed regionalization for this region so far.

Description of new bioregions follows the ICAN rules (Ebach et al., 2008). We formalize new bioregions, present synonymous areas (i.e., areas that have already been described but that had to be rearranged considering our results) and attribute a type locality to each unity.

3 | RESULTS

3.1 | Delimitation of bioregions

The data retrieved from the BFG revealed 1,748 angiosperm species endemics to the *campo rupestre* (See full list on Table S1 in Supporting Information). Data show that only c. 2% of all these species occur simultaneously in the *campo rupestre* of Goiás, Minas Gerais and Bahia states. Therefore, most species are endemic or microendemic to smaller areas in either the Espinhaço Range or in the Chapada dos Veadeiros.

From all species, 512 had only invalid, inaccurate or uncertain records from GBIF after data cleaning, so they were not included in the cluster analysis (see full list on Table S2 in Supporting Information).

From the remaining species endemic to *campo rupestre* (dataset one), we obtained 21,854 valid records in GBIF (Table S2). Alternatively, from the second working list considering all species in *campo rupestre* and adjacent areas (dataset two), we obtained 472,329 valid records of 12,724 species after data cleaning (see Tables S3 and S4 in Supporting Information).

Cluster analyses in both datasets always divided grid cells into at least two distinct clusters: one in the northern Espinhaço Range, in the state of Bahia, and one in the southern Espinhaço Range, in the state of Minas Gerais (Figure 2). A third cluster is formed in the area, corresponding to the Chapada dos Veadeiros region in the state of Goiás, but only when analysing just *campo rupestre* endemics
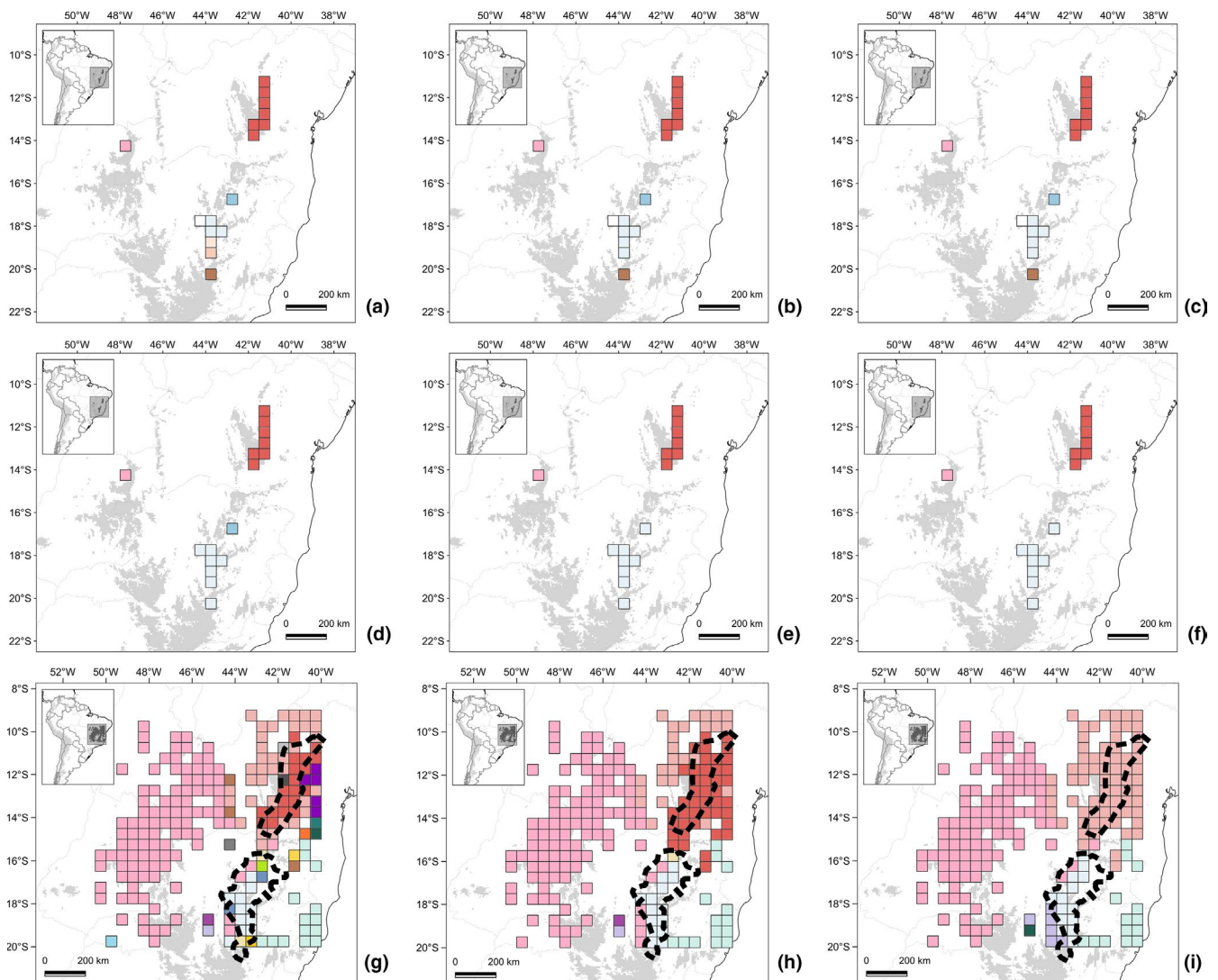
FIGURE 2 Summary of the analysis under different cluster costs from (a)–(f) only species endemic to *campo rupestre* (dataset one, totalizing 1,458 species) and (g)–(i) all species occurring in the study area (dataset two, totalizing 12,724 species), considering the minimum/maximum number of records per cell of 300. (a) and (g) are resulted from a cluster cost 1.0; (b)–(h) 1.2, (c)–(i) 1.4, (d) 1.6, (e) 1.8 and (f) 2.0. Note that figures (g) and (h) support the recognition of the northern portion of Espinhaço (reddish squares) and the Southern (purplish and bluish squares); the Chapada dos Veadeiros, however, is not clustered separately from the rest of the Cerrado portion (pink squares on the left of (i)). In order to facilitate the visualization of the bioregions and clusters, we outlined the new bioregions (see Figure 3) with a thick black line in (g)–(i). Cluster costs equal or greater than 1.6 from dataset two did not recover more than one bioregion, so they are not shown here. All information of most common and indicative species from all analyses can be found in Appendix S1–S3 (see Supporting Information). Figures S1 and S2 in Supporting Information shows the same result for the extant minimum/maximum records per cell values [Colour figure can be viewed at wileyonlinelibrary.com]
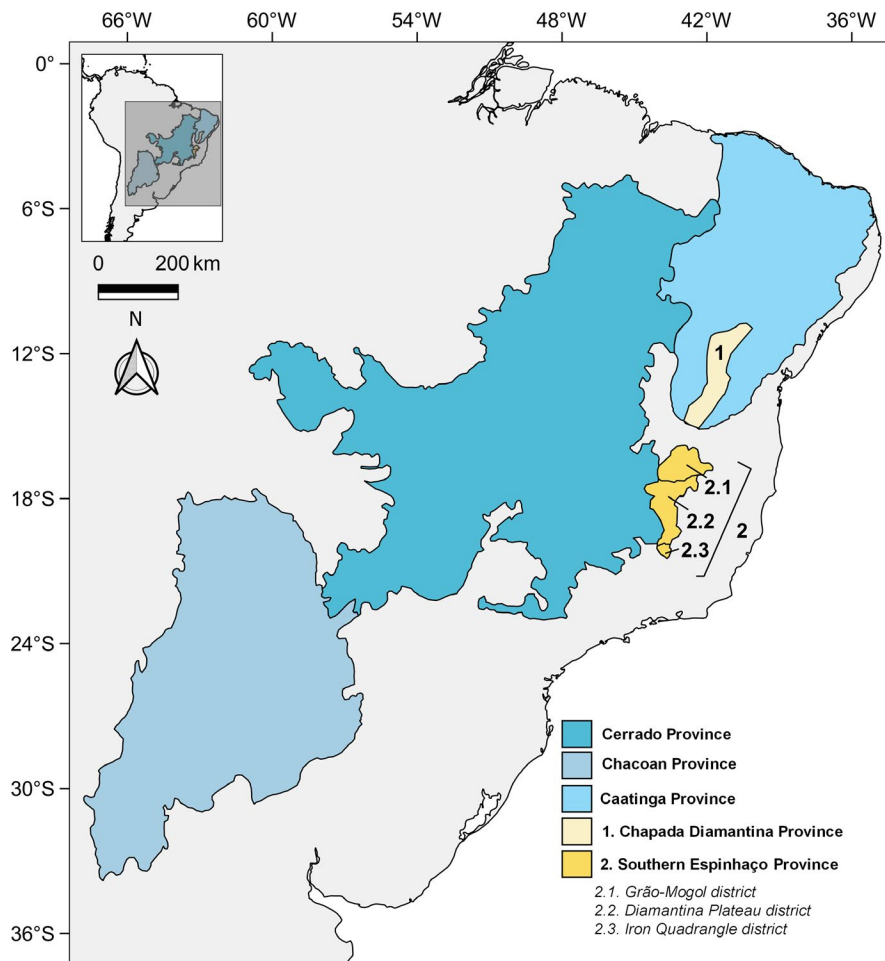
FIGURE 3 Formal delimitation of the two new bioregions in Eastern Brazil, based on distribution of the most indicative species analysed herein: provinces 1 and 2, the latter with districts, within Morrone's (2014) regionalisation of the Chacoan dominion. Shapefiles of these new bioregions are available on Appendix S4 in Supporting Information [Colour figure can be viewed at wileyonlinelibrary.com]

(Figure 2a–f). A fourth cluster on the Serra da Canastra region was also often recovered with laxer parameters (Figure 2g–i; see also Fig. S1 in Supporting Information to see this area considering laxer parameters).

Based on these results, there is a robust set of evidence to recognize two bioregions in the Espinhaço Range, as these clusters appear in all analyses with all combinations of datasets and parameters. As the bioregions are very singular and different from the vegetation and flora of the Cerrado and the Caatinga provinces, we decide to propose new provinces (not districts within previously existing provinces in Morrone's Chacoan dominion):

Chapada Diamantina province Colli-Silva, Vasconcelos and Pirani, *prov. nova.*

Campo rupestre phytochoria (*pro parte*) Prance, 1994.

Espinhaço Range region (*pro parte*) Giulietti et al., 1997.

Chapada Diamantina region (*pro parte*) (Bitencourt & Rapini, 2013).

Diagnosis. The narrow strip of the Espinhaço mountain range in Bahia state, Eastern Brazil, between 10°–15°S and 40°–43°W, mostly at altitudes above 900 m and covered by *campo rupestre* vegetation. (Figure 3). It corresponds to a portion here separated from the Caatinga province of Morrone's (2014) regionalization.

Type-locality. Chapada Diamantina National Park, Bahia, Brazil, 12°52′49″S 41°22′20″W.

Endemic taxa. See Appendix S1 and Tables S1 and S2 in Supporting Information.

Southern Espinhaço province Colli-Silva, Vasconcelos and Pirani, *prov. nova.*

Campo rupestre phytochoria (*pro parte*) (Prance, 1994).

Espinhaço Range region (*pro parte*) (Giulietti et al., 1997).

Serra do Espinhaço complex (Simon & Proença, 2000).

Southern Espinhaço region (*pro parte*) (Bitencourt & Rapini, 2013).

Diagnosis. The narrow strip of the Espinhaço mountain range in Minas Gerais state, Southeastern Brazil, from the Iron Quadrangle around Belo Horizonte north to the Grão-Mogol area, between 14°-16° S and 41°-44° W (Figure 3), mostly at altitudes above 900 m and covered by *campo rupestre* vegetation (Figure 3). It corresponds to a portion here separated from the Cerrado province of Morrone's (2014) regionalization.

Type-locality. Serra do Cipó State Park, Minas Gerais, Brazil, 16°36′51″S 42°57′22″W.

**Endemic taxa.** See Appendix S1 and Tables S1 and S2 in Supporting Information.

These two new provinces differ from each other regarding both their general floristic profiles and diversity of vegetational life forms. The Southern Espinhaço province is far richer in Eriocaulaceae and Velloziaceae species than the other province (Figure 4a), a fact that

(a) Floristic profile of endemic species in the Southern Espinhaço Province (n total = 1254)

(i) Family level

(ii) Genus level
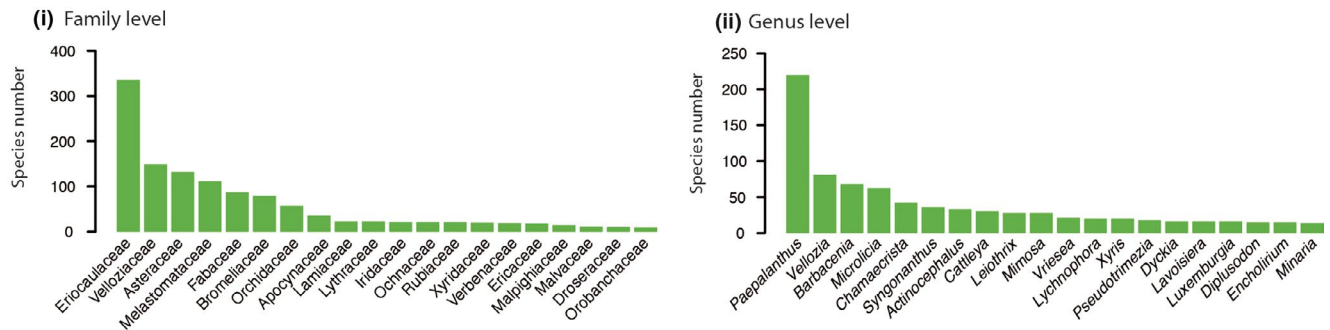
(b) Floristic profile of endemic species in the Chapada Diamantina Province (n total = 381)

(i) Family level

(ii) Genus level
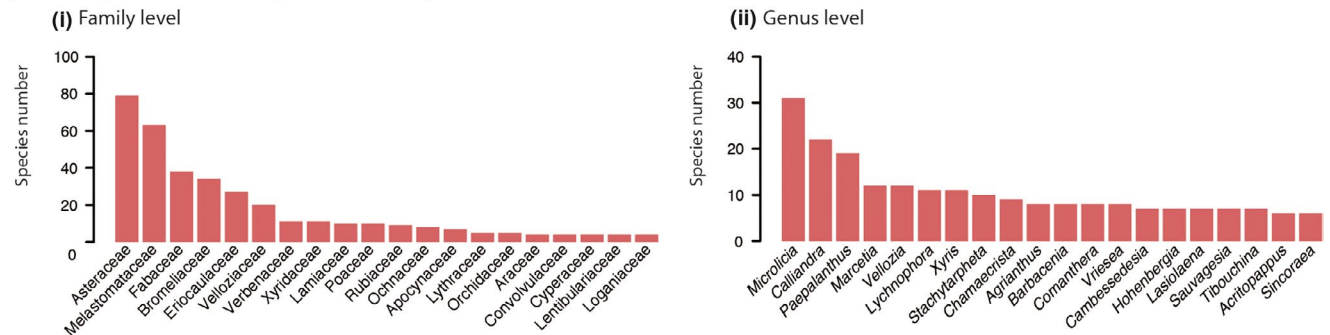
FIGURE 4 Summary of the most representative taxa from the two new provinces of *campo rupestre* at genus and family level, based on data from the BFG database [Colour figure can be viewed at wileyonlinelibrary.com]

reflects its higher abundance in herbs in contrast to the Chapada Diamantina province (Figure 5a). On the other hand, the Chapada Diamantina province is richer in members of the Leguminosae, Melastomataceae and Compositae families (Figure 4b) and shrubby (woody) species (Figure 5b).

3.2 | Delimitation of districts within the provinces

Within the Southern Espinhaço province, the species richest bioregion among the two described, we also recovered minor clusters when smaller values of cluster cost were used (see Figure 2a–c). In light of these results, we formalize three districts

within the Southern Espinhaço province, as described below. Those regions are similar to the ones found by Echternacht et al. (2011), so we formalize the same names as used by these authors. Bitencourt and Rapini (2013) also recovered different regions in the same portion of the Espinhaço Range based on Apocynaceae-Asclepiadoideae distribution data; they also distinguished the Iron Quadrangle and the Diamantina Plateau as different bioregions:

Grão-Mogol district Echternacht, Trovó, Oliveira and Pirani ex Colli-Silva, Vasconcelos and Pirani, *distr. novus.*

Northern Minas Gerais Region (*pro parte*) (Bitencourt & Rapini, 2013).

FIGURE 5 Summary of the prevalent life forms in each portion of *campo rupestre* (including the two new provinces), based on the BFG database [Colour figure can be viewed at wileyonlinelibrary.com]

Prevalent life forms of endemic species in each Province:

(a) Southern Espinhaço (n = 1254)

(b) Chapada Diamantina (n = 381)
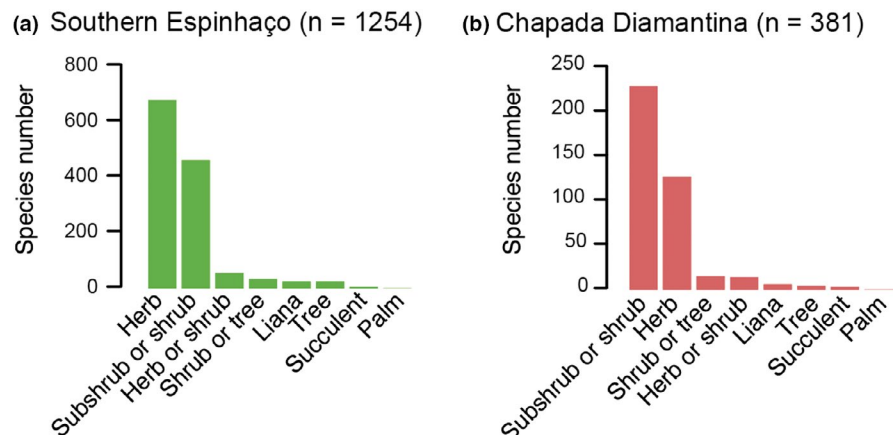
Diagnosis. The Northern polygon of the Espinhaço Range in Minas Gerais state, situated in the area of Grão-Mogol, Montes Claros, Monte Azul and Itacambira municipalities ("2.1" in Figure 3).

Type-locality. Grão-Mogol State Park, Minas Gerais state, Brazil, 16°36′51″S 42°57′22″W.

Endemic taxa. See Appendix S1 and S2 in Supporting Information. A more complete list is provided by Echternacht et al. (2011). A complimentary list of 59 angiosperm species endemic to this district is found in Pirani, Mello-Silva, and Giulietti (2003).

Diamantina Plateau district Echternacht, Trovó, Oliveira and Pirani ex Colli-Silva, Vasconcelos and Pirani, *distr. novus*.

Diamantina Plateau and Serra do Cipó Regions (*pro parte*) (Bitencourt & Rapini, 2013).

Diagnosis. The longer and wider central part of the Espinhaço Range in Minas Gerais state, including the Serra do Cipó, the Diamantina Plateau and the Serra do Cabral, situated in several municipalities ("2.2" in Figure 3).

Type-locality. Serra do Cipó State Park, Minas Gerais, Brazil, 19°20′57″S 43°37′10″W.

Endemic taxa. See Appendix S1 and S2 in Supporting Information. A more complete list is provided by Echternacht et al. (2011). A complimentary list of 197 vascular plant species endemic to the Serra do Cipó area within this district is found in Pirani et al. (2015).

Iron Quadrangle district Echternacht, Trovó, Oliveira and Pirani ex Colli-Silva, Vasconcelos and Pirani, *distr. novus*.

Southern Minas Gerais Region (*pro parte*) (Bitencourt & Rapini, 2013).

Diagnosis. The Southern polygon of the Espinhaço Range in Minas Gerais, corresponding to the region of Iron Quadrangle, which is composed of ironstone outcrops situated in the area of Belo Horizonte, Ouro Branco, Catas Altas and Moeda municipalities ("2.3" in Figure 2).

Type-locality. Belo Horizonte, Minas Gerais, Brazil, 19°49′01″S 43°57′21″W.

Endemic taxa. See Appendix S1 and S2 in Supporting Information. A more complete list is provided by Echternacht et al. (2011). A complimentary list of 60 angiosperm species endemic to this district is presented by Jacobi and Carmo (2012).

4 | DISCUSSION

4.1 | Formalizing *campo rupestre* bioregions

Since the creation of the ICAN in 2008, Morrone (2014) was one among few biogeographers who properly formalized bioregions in the Neotropics. Still, he did not recognize the areas focused herein as independent bioregions, merging them in the Chacoan dominion instead. A contrast can be traced with the Paramos in the northern Andes, a similar case of mountaintop vegetation with high levels of species endemism that was proposed as a distinct bioregion (Jiménez-Rivillas, García, Quijano-Abril, Daza, & Morrone, 2018; Morrone, 2015b). Morrone's bioregionalization is based on manual expert-delimitation using mainly zoological taxa distribution; sometimes, the delimitation of bioregions is also based on the congruence

between phytophysiognomic maps rather than strictly objective criteria such as clustering analysis. Consequently, the *campo rupestre* vegetation, well known for its outstanding floristic but not faunistic endemism levels, might have slipped through previous delimitations.

Besides the distinct endemism clusters that support the description of the two provinces here proposed, floristic profiles and prevalence of life forms in these two areas are also distinct. While the Chapada Diamantina province displays a mostly shrubby vegetational spectrum, the Southern Espinhaço province shows a mostly herbaceous one. This explains why different areas of *campo rupestre* can be classified either as shrublands or as grasslands, as recently debated by Mucina (2018). Furthermore, this demonstrates that not considering the herbaceous component of the *campo rupestre* vegetation leads to a biased view of its biodiversity. This is commonly done in phytosociological studies (e.g., Neves et al., 2018; Pontara et al., 2018) and can be problematic especially in the Southern Espinhaço province where the herbaceous component prevails in species diversity.

Lastly, this study highlights the *campo rupestre* areas as singular biogeographical entities that should not be treated simply as a part of the heterogeneity of the Cerrado ecoregion within the Chacoan dominion (as sometimes suggested by the literature, e.g., Simon & Proença, 2000; Proença et al., 2010). Supporting this, it is noteworthy that one of the new bioregions recognized herein, the Chapada Diamantina province, is not surrounded by the Cerrado province, but by the Caatinga province.

4.2 | Towards the recognition of minor-scale bioregions

Despite the existence of a few species with wide distribution on both provinces, our study has recovered two distinct *campo rupestre* provinces, and not a wider, single, unique and disjunct one, as first proposed by Prance (1994). Previous evidences had already shown that *campo rupestre* areas do not represent a single floristic group (Echternacht et al., 2011; Neves et al., 2018), and there may be also different assemblages of endemic species composing each of the two provinces and three districts proposed herein.

In this sense, we must point out that the so-called "archipelago" pattern that is so characteristic of montane formations (Prance, 1994), may often be related to distinct sets of endemic taxa in each "island". Consequently, it is likely that each region of the montane "archipelago" has also a particular evolutionary history and geobiotic scenario (as pointed out by Zappi et al., 2017), and thus different bioregions on different provinces of the Chacoan dominion should be further recovered.

4.3 | Advantages and limitations of big-data in the regionalization of *campo rupestre*

As our data are derived from GBIF, unprecise or dubious records are expected (Beck et al., 2014; Maldonado et al., 2015; Yesson et al., 2007) and some records could not be removed or corrected even through our data cleaning procedures. Still, two bioregions supported by previous empirical studies were strongly recovered. This

shows how GBIF data, although sometimes biased, still can allow a fair approximation of large spatial patterns (Maldonado et al., 2015). We must face we are now living in the "era of big-data" (Maldonado et al., 2015); thus, such databases can and should be used for such finalities – as long as some data cleaning procedures are taken beforehand. Manual expert taxonomic validation point by point is, of course, ideal and desirable, but sometimes it is absolutely unfeasible due to the enormous amount of data under analysis. In other words, this could be a redundant expenditure of time and resources.

Conversely, we must also stress that despite our results have recovered robust bioregions with considerable endemism levels regardless the set of cluster parameters selected, we believe these bioregions are still somehow underestimated. First, we believe the number of species supporting each bioregion would be even higher if record data were manually revisited, as we had to drop distribution data from over 500 species because of georeferencing errors.

Second, the Brazilian Flora 2020 Project is built by hundreds of taxonomists, and the definition of *campo rupestre* they use is not always the same. Due to historical reasons, it seems that taxonomists working in the Espinhaço Range are more likely to call those areas as *campo rupestre* than taxonomists working in the Chapada dos Veadeiros area (e.g., Pontara et al., 2018; M.F. Simon pers. comm.), despite the overall similarities of these landscapes. Besides, as the Brazilian Flora 2020 Project is yet to be finished, we noted that some species endemic to the *campo rupestre* are still missing from that database. As we strictly only considered the endemic species to the *campo rupestre* vegetation, other species listed in the BFG endemic to those regions but that were also listed to occur in other vegetations (e.g. rock outcrop vegetation, high altitude grasslands) were left aside.

Lastly, the Infomap Bioregions software also only lists the ten more indicative species, although there might be more than ten with the same or a slight lower indicative score. We decided to use those species only for the practical purpose of clearly circumscribing the bioregions; surely several remarkable species endemics to these bioregions were left out of this list. However, those, although not recovered as the most indicative, were all included in our datasets and can be found in the Supporting Information.

5 | CONCLUDING REMARKS

Results showing distinct endemism areas and floristic profiles are enthralling, as they can suggest that the components of the *campo rupestre* vegetation have evolved independently in different sets of mountaintops. High levels of endemism can result from two scenarios: either (a) these environments promote high local speciation (neoendemisms), or (b) they permit survival of lineages that undergo extinction elsewhere (palaeoendemisms) (Keppel et al., 2018). Even though *campo rupestre* have been classified as an old, climatically buffered and infertile landscape (Conceição et al., 2016; Hopper, Silveira, & Fiedler, 2015), thus intuitively associating them to palaeoendemisms, phylogenies of some endemic lineages have shown that recent, fast speciation is surprisingly common (e.g., Antonelli,

Verola, Parisod, & Gustafsson, 2010; Ribeiro, Rapini, Damascena, & Berg, 2014; Rando et al., 2016). There is certainly scope for further investigation on this question and we strongly believe that officializing these bioregions is going to facilitate such studies.

Such perception of convergent evolution in different areas traces us back to Humboldt's legacy of biological spectrum (Humboldt, 1806), evidencing how adaptations to similar climatic and altitudinal gradients shape plant morphology to similar forms along evolution. Despite their particular biogeographical histories, the outstanding vegetation of *campo rupestre* is floristically and ecologically unique. We advocate that by highlighting these patterns and establishing new bioregions, we emphasize the importance of conservation initiatives that help preserve this highly endemic and threatened flora in the future.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.