








## APPLICATION ARTICLE

# An assessment of methods to combine evolutionary history and conservation: A case study in the Brazilian campo rupestre

Raquel C. Pizzardo<sup>1,2</sup>  | Eimear Nic Lughadha<sup>3</sup>  | Juliana Gastaldello Rando<sup>4</sup>  |  
 Félix Forest<sup>3</sup>  | Anselmo Nogueira<sup>5</sup>  | Luana S. Prochazka<sup>5,6</sup>  |  
 Barnaby E. Walker<sup>3</sup> | Thais Vasconcelos<sup>2</sup> 

<sup>1</sup>Laboratório de Sistemática Vegetal, Departamento de Botânica, Universidade de São Paulo, São Paulo, São Paulo, Brazil

<sup>2</sup>Department of Ecology and Evolutionary Biology, University of Michigan, Ann Arbor, Michigan, USA

<sup>3</sup>Royal Botanic Gardens, Kew, Richmond TW9 3AE, United Kingdom

<sup>4</sup>Programa de Pós-Graduação em Ciências Ambientais, Centro das Ciências Biológicas e da Saúde, Universidade Federal do Oeste da Bahia, Barreiras, Bahia, Brazil

<sup>5</sup>Laboratório de Interações Planta-Animal (LIPA), Centro de Ciências Naturais e Humanas, Universidade Federal do ABC, São Bernardo do Campo, São Paulo, Brazil

<sup>6</sup>Programa de Pós-graduação em Biodiversidade Vegetal e Meio Ambiente, Instituto de Pesquisas Ambientais, São Paulo, São Paulo, Brazil

## Correspondence

Raquel C. Pizzardo, Department of Ecology and Evolutionary Biology, University of Michigan, Ann Arbor, Michigan, USA.  
 Email: [pizzardo@umich.edu](mailto:pizzardo@umich.edu)

This article is part of the special issue “From Theory to Practice: New Innovations and Their Application in Conservation Biology.”

## Abstract

**Premise:** Conservation policies typically focus on biodiversity hotspots. An alternative approach involves analyzing the evolutionary history of lineages in geographic areas along with their threat levels to guide conservation efforts. Mountains exhibit high levels of plant species richness and micro-endemism, and biogeographic studies commonly point to recent and rapid evolutionary radiations in these areas. Using a nearly endemic clade of legumes, our study evaluates conservation prioritization approaches in the campo rupestre, a Neotropical ecosystem associated with mountaintops that is located between two biodiversity hotspots.

**Methods:** We compared the EDGE and EDGE2 metrics, which combine the evolutionary distinctiveness and the extinction risk of a species in a single value. These metrics are compared with traditional metrics used to assess conservation priority, such as phylogenetic diversity.

**Results:** The EDGE values reported are lower than those of other studies using this metric, mostly due to the prevalence of threatened species with short phylogenetic branch lengths (low values of evolutionary distinctiveness). Certain areas of campo rupestre with relatively high phylogenetic diversity and EDGE values do not correspond to areas with high species richness, agreeing with previous studies on biodiversity hotspots.

**Discussion:** Our study highlights the necessity of conservation of the campo rupestres as well as advantages and disadvantages of using EDGE, EDGE2, and phylogenetic diversity for appropriate selection of conservation areas with rapid evolutionary radiations. The selection of the metrics will depend primarily on the life history of the focus group and the data availability, as well as the conservation approach.

## KEYWORDS

campo rupestre, *Chamaecrista*, EDGE, EDGE2, mountain range, phylogenetic diversity

Global biodiversity is under extreme pressure because of human activities, and the decline in plant diversity is particularly noticeable (Butchart et al., 2010; Nic Lughadha et al., 2020). About 40% of all plant species are estimated to be threatened with extinction, with the main threats being habitat transformation and harvesting (Nic Lughadha

et al., 2020). Furthermore, the estimated rate of ongoing seed plant extinction in the Anthropocene is conservatively estimated at up to 500 times the background rate for plants (Humphreys et al., 2019). When so many species face severe threats, choosing which ones deserve the most conservation effort is difficult, especially in areas with

This is an open access article under the terms of the [Creative Commons Attribution-NonCommercial](https://creativecommons.org/licenses/by-nc/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

© 2024 The Authors. *Applications in Plant Sciences* published by Wiley Periodicals LLC on behalf of Botanical Society of America.

limited resources and numerous threats, such as the tropics (Pimm et al., 2001).

Tropical mountains are areas with high levels of endemism and are under constant pressure due to climate changes and habitat transformation (Orme et al., 2005; Antonelli et al., 2020). These areas are speciose and tend to be either hotspots for the origin of new species or refugia for species survival, accumulating both old, depauperate lineages and recent, rapidly diversifying ones (Stewart et al., 2010; Vasconcelos et al., 2020). In eastern Brazil, the campo rupestre is a mountain ecosystem with all the features mentioned above. Described over the years as an ecosystem of outstanding plant richness and endemism levels (Giulietti and Pirani, 1988; Bitencourt and Rapini, 2013; Moro et al., 2015; Colli-Silva et al., 2019), the campo rupestre hosts 15% of all Brazilian vascular plants in 0.78% of the country's territory (Silveira et al., 2016). It is located between two biodiversity hotspots, the Cerrado and the Atlantic Forest, as well as the Caatinga (seasonally dry forest) domain (Giulietti and Pirani, 1997; Zappi et al., 2003; Rapini et al., 2008; Conceição et al., 2016; Colli-Silva et al., 2019). Although the campo rupestre is to a certain extent protected under some Conservation Units (see <https://cnuc.mma.gov.br/map> for a list of Conservation Units in Brazil), its high diversity and habitat heterogeneity contribute to an ongoing need for conservation efforts (Silveira et al., 2016).

Approaches that consider biodiversity hotspots (i.e., areas with an exceptionally high concentration of endemic species that are undergoing loss of habitat; sensu Myers et al., 2000) are commonly used to identify regions for conservation (Myers et al., 2000; Wilson et al., 2006; Allen, 2008; Cartwright, 2019), and such approaches have been applied to the campo rupestre (e.g., Echternacht et al., 2011; Inglis and Cavalcanti, 2018; Colli-Silva et al., 2019; Pacifico et al., 2020). These are effective methods, but preserving the evolutionary history of lineages is also essential, requiring approaches that incorporate evolution into conservation priorities (Mace et al., 2003). Phylogenetic diversity (PD) is a biodiversity metric that measures the length of evolutionary pathways that connect a given set of taxa in a phylogenetic tree (Faith, 1992). PD is also expected to be a good surrogate of feature diversity, so higher PD may indicate more resilient species and ecosystems that should be prioritized for conservation (Faith, 1992; Forest et al., 2007). In the campo rupestre, previous studies have described centers of PD for several groups using different metrics (e.g., Zappi et al., 2017; Cortez et al., 2021), and they frequently match areas of endemism previously identified in the region.

Although PD is an important tool for conservation, one should ideally be able to combine evolutionary history and the level of threat faced by species in one area, but the latter is not captured by PD. The Evolutionarily Distinct and Globally Endangered (EDGE) method was developed to fill this gap, incorporating phylogenetic information into conservation prioritization by combining an evolutionary distinctiveness (ED) index and a global endangerment (GE) score, the latter based on the International Union for Conservation of Nature (IUCN) Red List category of extinction risk (Isaac et al., 2007). The IUCN Red List is an internationally recognized tool that

supports conservation planning by providing data on the level and type of threats faced by species and assigning them a threat category determined by applying a standard and internationally recognized set of criteria (IUCN, 2022). The criteria A to E apply a range of approaches to assess the threat category of a particular species. In other words, both the IUCN Red List category and the evolutionary distinctiveness of species in an area are relevant when selecting which species or areas to preserve, and EDGE is a metric that combines the two.

The EDGE method has proven successful in animal groups, enabling the identification of species that are threatened and have few or no close relatives on the tree of life (Isaac and Pearse, 2018). For plants, the first clade to benefit from the EDGE approach was the cycads (Yessoufou et al., 2017), followed by broader analyses of gymnosperms, one of the most threatened groups of living organisms (40% of species at high risk of extinction; Forest et al., 2018). In Asia, the EDGE approach has been applied to orchids at a regional level (Li et al., 2018). For *Dioscorea* Plum. ex L. (Dioscoreaceae) species in South Africa, species distribution modeling (SDM) was combined with EDGE scores to produce species richness (SR), extinction risk (ER), ED, and EDGE diversity maps to inform area prioritization for conservation (Hills et al., 2019). More recently, EDGE2 was developed based on probabilistic approaches to quantify the avertable loss of PD through phylogenetically informed conservation policies that focus on individual species (Gumbs et al., 2023). This metric allows the assignment of ER scores for all species, including the Data Deficient (DD) and unassessed ones (Not Evaluated [NE]; Gumbs et al., 2023). However, no comparative studies applying all these metrics have focused on the Neotropics, a global center of floristic diversity and the region with the largest number of vascular plant species in the world (Ulloa et al., 2017; Raven et al., 2020; BFG, 2021).

This study aims to evaluate conservation prioritization approaches in the campo rupestre, contrasting three metrics used to factor evolutionary history into conservation prioritization: EDGE, EDGE2, and PD. We use *Chamaecrista* (L.) Moench ser. *Coriaceae* (Benth.) H. S. Irwin & Barneby, a group nearly endemic to the campo rupestre, as a case study to compare the effectiveness of these methods. We assess the conservation status of all 19 species in the clade and rank their conservation priority using the EDGE and EDGE2 methods. We compare areas of high SR, PD, EDGE, and EDGE2 for the group based on previously described areas of endemism in the region. Because of the differences in how PD, EDGE, and EDGE2 are calculated, we expect to see differences in the distribution of these three metrics across the campo rupestre, with implications for conservation prioritization.

## METHODS

### *Chamaecrista* ser. *Coriaceae* as a model group

Leguminosae is one of the most diverse angiosperm families in the campo rupestre (Colli-Silva et al., 2019). The presence of a

high number of legume species and their high endemism levels make some Leguminosae lineages good model systems for ecological and evolutionary studies in this ecosystem, where the flora is characterized by a mosaic of species with different adaptations and multiple biogeographic origins (Silveira et al., 2016). One such legume lineage is *Chamaecrista*, for which the Cerrado and campo rupestre are the main centers of diversity with a considerable number of endemic species (about 225 species in the Cerrado and 173 species in the campo rupestre; Irwin and Barneby, 1978, 1982; Rando et al., 2020; BFG, 2021). *Chamaecrista* is also one of Brazil's most species-rich lineages, with 268 species occurring in the country (Rando et al., 2020).

The infrageneric classification of *Chamaecrista* comprises a division into sections and series (Irwin and Barneby, 1982; Conceição et al., 2009). Among them, *Chamaecrista* sect. *Chamaecrista* ser. *Coriaceae* is a monophyletic series recognized by its reduced axillary inflorescences, presence of extrafloral nectaries, woody underground system, and one stamen displaced adjacent to the style (Rando et al., 2016, 2019). This series comprises 19 species, forming a clade that is near endemic to the campo rupestre, restricted to the geographical area of the Espinhaço Mountain Range or adjacent higher-elevation areas (except for *C. mucronata* (Spreng.) H. S. Irwin & Barneby, disjunct between the Espinhaço Mountain Range and the coastal restinga vegetation in Espírito Santo state; Figure 1). We chose *Chamaecrista* ser. *Coriaceae* for this study because it is a well-sampled clade that is almost entirely restricted to campo rupestre vegetation, has a recent and comprehensive taxonomic revision (Rando et al., 2019), and has a complete time-calibrated phylogenetic tree (Rando et al., 2016).

## IUCN Red List assessments

We constructed a data set of occurrences for the 19 species in the group using the publicly available specimen databases speciesLink (<https://splink.cria.org.br/>) and Reflora (<http://floradobrasil.jbrj.gov.br/>), new field collections (deposited in the Universidade de São Paulo herbarium), and a recent taxonomic revision of the group (Rando et al., 2019). All occurrence records were manually cleaned by removing duplicates and records without expert identification or precise locality (e.g., georeferenced as centroids of municipalities and no locality description in the specimen voucher), and were georeferenced as accurately as possible when the coordinates were not available. The georeferenced occurrences were obtained by checking the locality description on the specimen's labels and locating that locality in Google Earth (Google, Mountain View, California, USA) (Appendix S1).

Using this curated data set of distribution points (568 unique localities), we assessed ER for all *Chamaecrista* ser. *Coriaceae* species with maximum accuracy, following the IUCN Red List criteria (IUCN, 2022). Criterion B was the most suitable and easily applicable. Criterion B was designed to detect populations that have restricted distribution and are

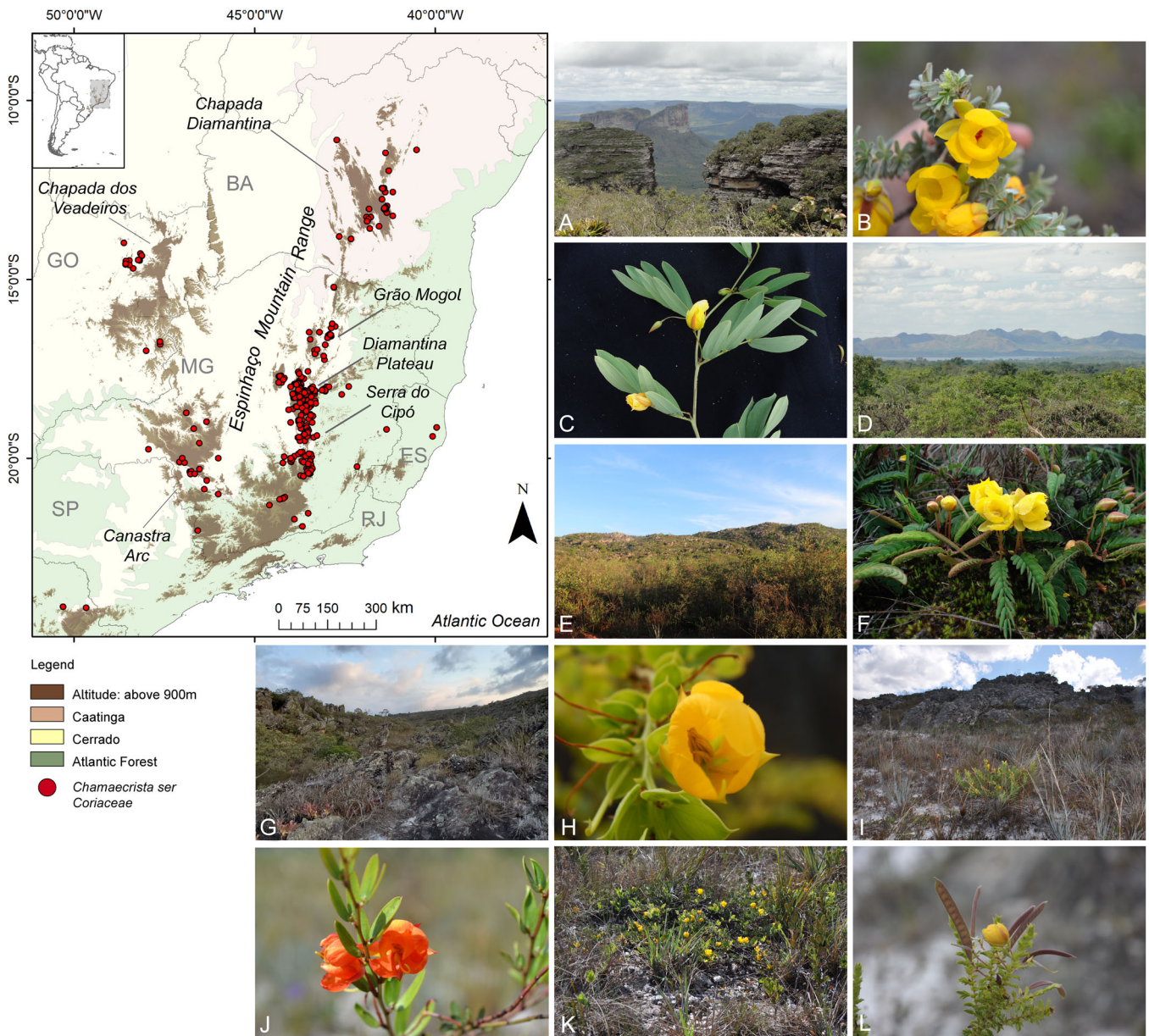
also severely fragmented or have few occurrence points. This evaluation is made by calculating the Extent of Occurrence (EOO) and Area of Occupancy (AOO). The population must also show decline or fluctuations to justify the classification at IUCN threatened categories (Vulnerable [VU], Endangered [EN], or Critically Endangered [CR]; IUCN Standards and Petitions Committee, 2022). However, because of the lack of population information for most species, including those of *Chamaecrista* ser. *Coriaceae*, criterion B can be wrongly applied. Thus, in addition to calculating the EOO and AOO, we used information regarding threats that the populations face in each locality that could lead to population fluctuation (e.g., habitat fragmentation in response to human land use).

In the context of the species analyzed here, we assumed that the most plausible threats to potential loss of population size in the near future are those known to impact other campo rupestre–endemic lineages. According to the *Plano de Ação Nacional para a Conservação da Flora Ameaçada de Extinção da Serra do Espinhaço Meridional* (PAN; Pougy et al., 2015a), the most relevant threats for the flora in the area are mining, fire, agriculture, livestock, human occupancy (urban sprawl and tourism), invasion of exotic species, and extraction of non-timber forest products. To evaluate these threats in the context of *Chamaecrista* ser. *Coriaceae* distribution, we assessed whether these threats co-occur with the species distribution by visualizing which threats are recorded for the campo rupestre area. For this purpose, we downloaded mining and human occupancy data from the Instituto Brasileiro de Geografia e Estatística (IBGE) database (resolution of 1 km<sup>2</sup>; <https://www.ibge.gov.br/>), formatted as points of occurrence of mining, built-up areas, and towns. Regarding agriculture and livestock, we consulted a thematic map, also from IBGE. For fire data occurrence, a shapefile was downloaded from the National Aeronautics and Space Administration (NASA) Fire Information for Resource Management System (FIRMS; [https://firms.modaps.eosdis.nasa.gov/active\\_fire](https://firms.modaps.eosdis.nasa.gov/active_fire)) with near real-time data with about a 2–3-month lag. To obtain data regarding invasion of exotic species, distribution points of *Urochloa* P. Beauv. spp. (Poaceae), a well-established exotic grass in the area, were retrieved from speciesLink and added to the map for visual inspection. *Urochloa* spp. were introduced in the area primarily for their use in livestock and are well known for outcompeting native plant species in the campo rupestre (Pougy et al., 2015a). Finally, because none of the studied species are considered ornamental or of immediate economic interest, we did not analyze the threat of extraction of non-timber products (Appendix S2).

## Species distribution modeling

We produced SDMs for all the species using the curated data set of distribution points, intending to fill the gaps in species distribution via extrapolations using environmental variables. The species presence estimations were based on the suitability of habitats, seeking to minimize both commission and omission errors when species are mistakenly thought to be





**FIGURE 1** Map (upper left) showing the geographic distribution of the 19 species of *Chamaecrista* ser. *Coriaceae* (red dots) in the study area. The brown shading indicates elevation above 900 m, and the pink, yellow, and green shadings represent the Caatinga, Cerrado, and Atlantic Forest domains, respectively. Area names in *italics* are areas of endemism frequently identified in campo rupestre floristic studies. (A) Morro do Pai Inácio, an area of campo rupestre in the Chapada Diamantina, Bahia (BA); (B) *C. tragacanthoides*, branch with flowers; (C) *C. burchellii*, branch with flowers; (D) Niquelândia area, part of Chapada dos Veadeiros, Goiás (GO); (E) Grão Mogol area, Minas Gerais (MG); (F) *C. olesiphylla*, branch with flowers; (G) Diamantina Plateau, an area of campo rupestre in Minas Gerais (MG); (H) *C. aristata*, branch with flower; (I) habit of *C. rossicorum*; (J) *C. simpliflora*, branch with flowers; (K) habit of *C. arrojadoana*; (L) *C. distichoclada*, branch with flower and fruit. Photo credits: J. G. Rando (A, C, D, F), M. Cota (B, J), J. C. Lopes (E), R. C. Pizzardo (G, L), A. Nogueira (H), T. Vasconcelos (I, K). ES, Espírito Santo; RJ, Rio de Janeiro; SP, São Paulo.

present or absent in an area, respectively, and thereby reduce the risk of overestimating or underestimating areas where the species are distributed (e.g., Hills et al., 2019). This approach helps reduce the possibility of erroneously identifying regions as conservation priority areas.

To do this, we used layers of 19 climatic variables obtained from CHELSA Bioclim (Karger et al., 2017) at a high resolution of 30 arcsec. We then performed a multicollinearity

test among the 19 variables to detect a strong correlation between them and avoid overestimating the contribution of inter-correlated environmental features under the distribution points, using the function *vif* from the R package *usdm* (Naimi et al., 2014; R Core Team, 2022) with a threshold of 0.8. We excluded highly collinear layers from the analyses, resulting in a data set of eight variables, four for temperature and four for precipitation. Those were: Mean Diurnal Range (BIO02),

Temperature Annual Range (BIO07), Mean Temperature of Wettest Quarter (BIO08), Mean Temperature of Driest Quarter (BIO09), Precipitation of Wettest Month (BIO13), Precipitation of Driest Month (BIO14), Precipitation of Warmest Quarter (BIO18), and Precipitation of Coldest Quarter (BIO19).

To avoid the biased representation of species distribution that could result from using just one algorithm (Peterson et al., 2011), we combined four algorithms to obtain models with high explanatory power: generalized linear model (GLM), random forest, boosted regression trees (BRT), and MaxEnt (maxent; Phillips et al., 2006), generating ensemble models for each species. The models were generated using the R package *sdm* with five replicates for each algorithm per species (Naimi and Araújo, 2016). One thousand random background points were generated for each modeling analysis. Model validation was undertaken using the bootstrap method, with default settings for validation. The evaluations of the ensemble models relied on the true skill statistic (TSS) and the area under the receiver operating characteristic curve (AUC), both considered effective for this kind of analysis (Allouche et al., 2006). Because we analyzed species with a relatively restricted distribution (i.e., only occurring within a relatively small biogeographical region), only models with TSS and AUC values equal to or higher than 0.8 were considered high-performance models and used in this study.

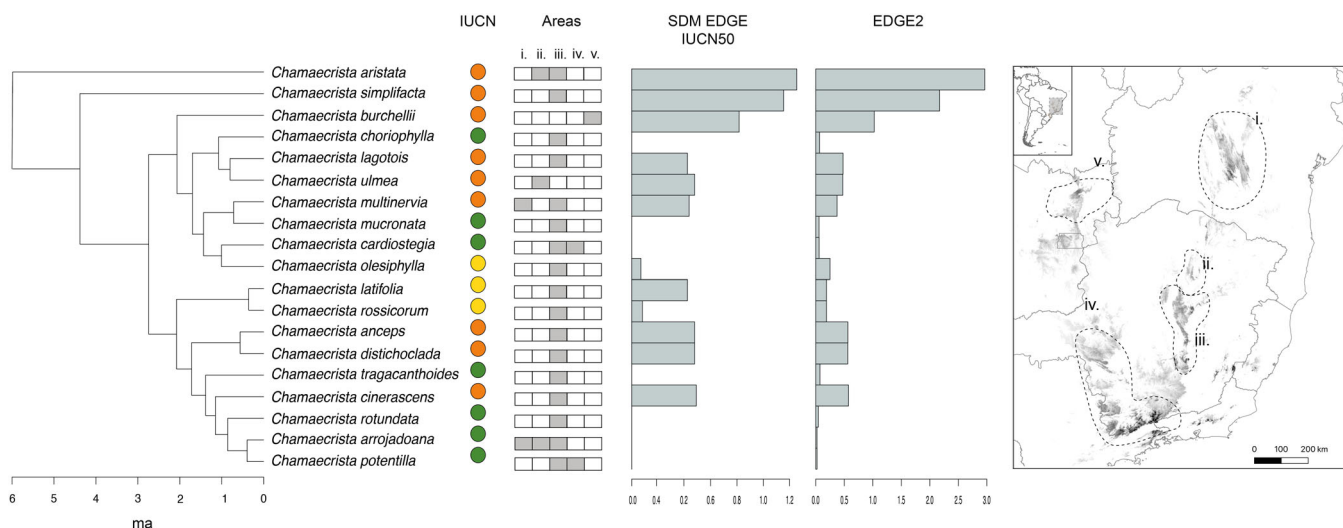
To combine SDM outputs with values of the metrics calculated herein (EDGE, EDGE2, ED, SR, and PD), we created a presence/absence matrix with a suitability threshold of 0.5 for all the models representing the 19 species in *Chamaecrista* ser. *Coriaceae* using R (R Core Team, 2022). Thus, for all 19 models, each grid cell (30 arcsec, ~1 km) with a suitability value equal to or higher than 0.5 was considered a presence grid for that species. We

chose the 0.5 threshold after exploratory tests showed that it was the maximum value that allowed us to include all analyzed species in the subsequent analyses. To verify how this threshold of 0.5 would impact our analyses, we also ran sensitivity tests with a range of threshold values to verify how this value would affect our results (Appendix S3). We then used the presence/absence matrix to create the maps for each metric combined with the most likely distribution of each species.

## Biodiversity metrics: PD, ED, EDGE, and EDGE2 calculations

Biodiversity metrics were calculated using a modified time-calibrated phylogenetic tree of *Chamaecrista* inferred by Rando et al. (2016) (Figure 2), pruned to include only species of the focal clade. Here, we are evaluating conservation priorities in the sense of survival and resilience of the species, hence the use of a chronogram for PD and the other diversity estimations (Kling et al., 2018). *Chamaecrista multinervia* (Mart. ex Benth.) H. S. Irwin & Barneby was imputed as the sister species to *C. mucronata* based on its morphology and unpublished results of a phylogenetic analysis that sampled this species. This tip was assigned using the function *bind.tip* from the R package *phytools* (Revell, 2023) using half of the *C. mucronata* terminal branch length. Sensitivity tests were conducted, exploring the impact on our main results of excluding or including *C. multinervia* with varying branch lengths from its sister species (Appendices S3, S4).

We calculate the PD as the sum of branch lengths connecting the root of the phylogenetic tree to all species (tips of the phylogenetic tree) present in each grid cell



**FIGURE 2** Dated tree of *Chamaecrista* sect. *Chamaecrista* ser. *Coriaceae* (left) (ma = millions of years ago). IUCN Red List assessments are color-marked on the right of the tree (orange: Endangered; yellow: Vulnerable; green: Least Concern). Areas (i to v) indicate the five areas of endemism described for the campo rupestre flora (corresponding to the map on the right): (i) Chapada Diamantina, (ii) Grão Mogol, (iii) Diamantina Plateau and Serra do Cipó, (iv) Canastra Arc, (v) Chapada dos Veadeiros. EDGE and EDGE2 scores are represented as barplots.



(Faith, 1992) using the function *pd* of the R package *picante* (Kembel et al., 2010). ED scores for all the species were obtained using the function *evol.distinct* of the R package *picante* (Kembel et al., 2010). The EDGE and EDGE2 values were calculated using the equations described below, with the scores compiled for the 19 species using the tree described above.

There are various methods to account for probability of extinction in the compilation EDGE values, with no consensus on which is the most appropriate (Moors et al., 2008; Isaac et al., 2012). We compared the two most common approaches, (1) ISAAC and (2) IUCN50. The ISAAC method (Isaac et al., 2007) was applied using the following IUCN categories conversion for GE (Red List category weight; IUCN, 2022) values and the EDGE equation: Least Concern (LC) = 0, Near Threatened (NT) = 1, VU = 2, EN = 3, CR = 4.

$$EDGE_{ISAAC} = \ln(1 + ED) + GE * \ln(2) \quad (1)$$

The IUCN50 transformation (Moors et al., 2008) has the following IUCN categories conversion for ER (i.e., the probability of extinction) values and the EDGE equation: LC = 0.00005, NT = 0.004, VU = 0.05, EN = 0.42, CR = 0.97.

$$EDGE_{IUCN50} = \ln(ED * ER) \quad (2)$$

As EDGE is a logarithmic equation, IUCN50 transformation can produce negative values because the ER values are lower than 1. Negative values can be problematic for map construction, so we altered the formula by adding a constant value (+1), which does not affect the EDGE ranking. The final equation used was  $EDGE_{IUCN50} = \ln(ED * ER + 1)$  (Hills et al., 2019).

In the case of EDGE2, the GE2 and ED2 metrics are implemented (Gumbs et al., 2023). ED2 is a weighted version of ED that accounts for the probability of extinction of species closely related to the focal species. The metric includes the probability (*p*) of extinction for each species (*i*), such that  $GE2_i = p_i$ . Thus  $ED2_i = TBL_i + \sum_{j=2}^{n_i} (L_{ij} * \prod_{k \in C_{i,j}-\{i\}} P_k)$ , where  $L_{i,j}$  is the branch length of species *i*,  $C_{i,j}$  represents all species descended from the corresponding branch with length  $L_{i,j}$ , and *p* the probability of extinction of species *k*. This approach incorporates PD complementarity in ED2, which means that the ER of close relatives is accounted for. Finally, the formula for EDGE2 is the following:

$$EDGE2 = ED2 * GE2 \quad (3)$$

## Diversity maps

To produce a map of SR for *Chamaecrista* ser. *Coriaceae*, we used the *Reduce* function in R version 4.2.1 (R base; R Core Team, 2022), which combines the elements of the binary maps resulting from the SDM analyses. The ED, ER, EDGE, EDGE2, and PD maps were produced following a similar

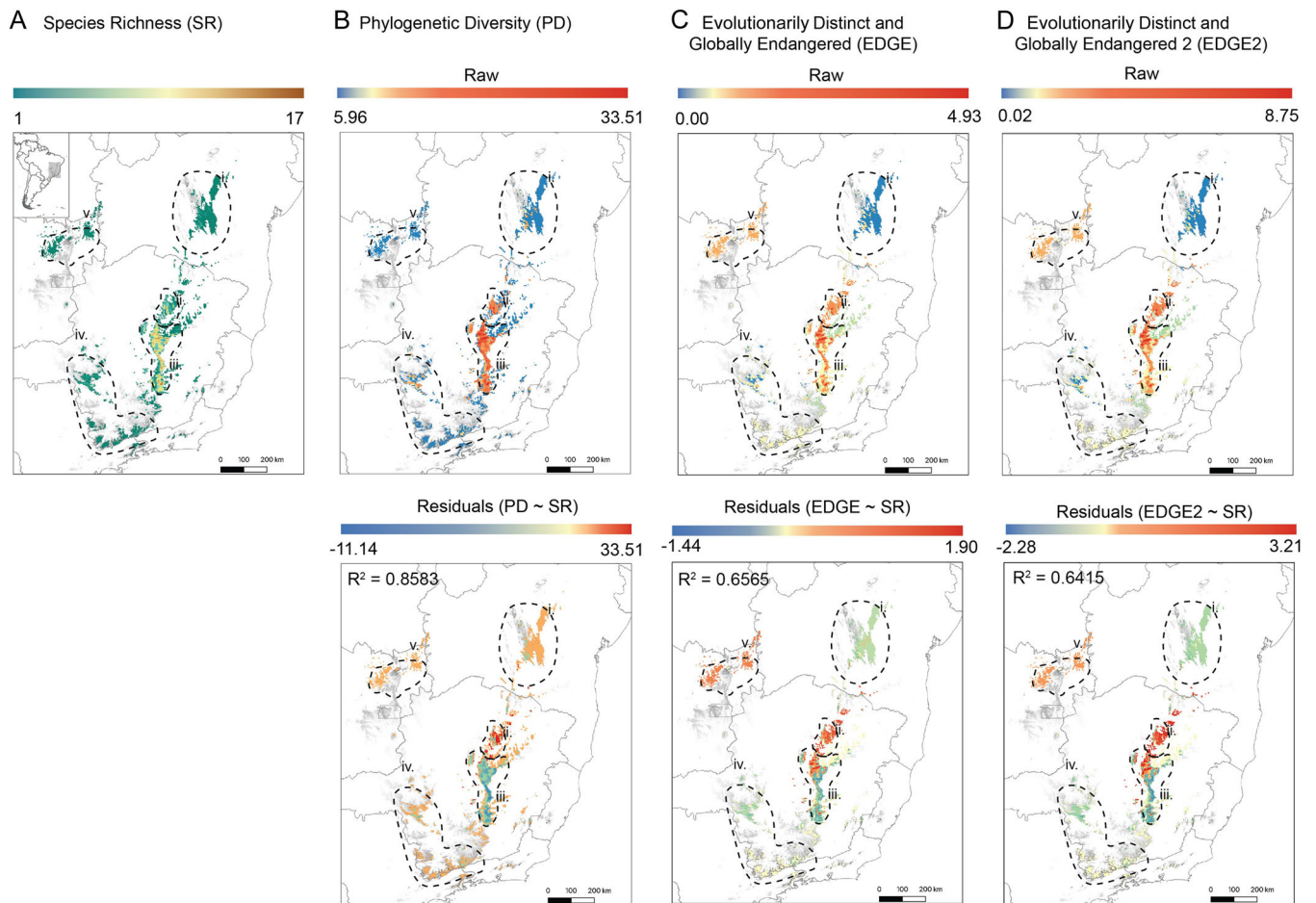
approach. These maps resulted from the sum of the values of the metrics for each species presented in each cell of the map. For the EDGE map, we considered only the IUCN50 transformation. Compared to the ISAAC transformation, the IUCN50 attributes a lower ER to non-threatened species and a higher one to threatened species, thus best reflecting the high levels of threatened species for this analysis (Forest et al., 2018). All the maps were imported and manipulated using the QGIS Geographic Information System tools (<http://www.qgis.org>). The SR map was constructed using the natural breaks classification to facilitate comparisons between maps, while the quantile classification was used for the other maps. Also, because EDGE, EDGE2, and PD are expected to positively correlate with SR in all cases (e.g., regions with higher SR will tend to have higher values of those metrics), we analyzed the residuals from linear regressions where each index was set as a response variable, while SR was used as a predictor variable (e.g.,  $PD \sim SR$ ,  $EDGE \sim SR$ ,  $EDGE2 \sim SR$ ).

Previous studies have grouped floristically unique areas within the campo rupestre (e.g., Echternacht et al., 2011; Inglis and Cavalcanti, 2018; Pacifico et al., 2020). These studies present different arrangements of endemism areas depending on the study group, but they generally agree that at least five areas can be recognized (Figure 1): Chapada Diamantina, Grão Mogol, Diamantina Plateau, Chapada dos Veadeiros, and Canastra Arc (with Grão Mogol and the Diamantina Plateau placed in the Southern Espinhaço Province sensu Colli-Silva et al., 2019). To evaluate areas of priority for conservation of *Chamaecrista* ser. *Coriaceae*, we discuss the contrast between SR,  $PD \sim SR$  residuals,  $EDGE \sim SR$  residuals, and  $EDGE2 \sim SR$  residuals in the context of these five areas.

## RESULTS

### Mapping the evolutionary diversity in the campo rupestre

All the SDMs produced by the four algorithms resulted in AUC and TSS values equal to or higher than 0.8 for all species, except for *C. cardiostegia* H. S. Irwin & Barneby (TSS of 0.776 for BRT) and *C. multinervia* (TSS of 0.706 for GLM). Both the EDGE and EDGE2 maps generally exhibited similar patterns (Figure 3), highlighting the same areas with high values for both metrics. There was congruence in the distribution of the raw ER, ED, PD, EDGE, and EDGE2 values in the diversity maps and similarity to the SR distribution per cell (Figure 3, Appendix S5). The SR map shows the maximum number of species per cell in the southern Espinhaço Mountain Range, especially in the Serra do Cipó and Diamantina Plateau regions, with lower but still evident diversity in the Grão Mogol region. SR varies between one and 17 co-occurring species per cell, while ER varies between 0.04 and 3.09, ED from 0.75 to 31.97 (see Appendix S3), PD from 5.91 to 33.51, EDGE from 0.00 to 4.93, and EDGE2 from



**FIGURE 3** Diversity maps for the 19 species of *Chamaecrista* sect. *Chamaecrista* ser. *Coriaceae*. (A) Species richness (SR); (B) phylogenetic diversity (PD), showing raw PD values (top) and associated residuals with SR (bottom); (C) Evolutionarily Distinct and Globally Endangered (EDGE), showing raw EDGE values (top) and associated residuals with SR (bottom); (D) Evolutionarily Distinct and Globally Endangered 2 (EDGE2), showing raw EDGE2 values (top) and associated residuals with SR (bottom). Areas (i to v) indicate the five areas of endemism described for the campo rupestre flora (corresponding to the map in Figure 2): (i) Chapada Diamantina, (ii) Grão Mogol, (iii) Diamantina Plateau and Serra do Cipó, (iv) Canastra Arc, (v) Chapada dos Veadeiros.

0.02 to 8.75. Although maximum values of ED also highlight the southern Espinhaço Mountain Range, the map slightly emphasizes the northern Espinhaço Mountain Range (i.e., Chapada Diamantina endemism region; Appendix S5).

The residual maps indicate that cells in the Grão Mogol region have the highest values for PD, EDGE, and EDGE2 compared to what can be predicted from their SR alone, corroborating the importance of this area to the evolutionary diversity of *Chamaecrista* ser. *Coriaceae* in the campo rupestre. However, EDGE and EDGE2 residuals also highlight the northern part of the Diamantina Plateau, which is not as strongly highlighted by PD residuals. The Chapada dos Veadeiros region also seems to present relatively high values of EDGE and EDGE2 residuals, but this is driven by the distribution of a single species in that region (*C. burchellii* (Benth.) H. S. Irwin & Barneby).

Results from sensitivity tests exploring different threshold values for the SDM analyses show that the estimated distribution range of a species varies considerably depending on the threshold used. Lower threshold

values result in extensive ranges, whereas values above 0.5 reduce the range as the threshold value increases. For some species, depending on the value, the ranges disappear completely (Appendix S3).

### Conservation priority in *Chamaecrista* ser. *Coriaceae*

Of the 19 species assessed, 12 are evaluated as threatened (Table 1). None are categorized as CR, nine are EN, and three (*C. latifolia* (Benth.) Rando, *C. rossicorum* (H. S. Irwin & Barneby) Rando, and *C. olesiphylla* (Vogel) H. S. Irwin & Barneby) are VU. The other seven species are categorized as Least Concern (LC). Surprisingly, ED and IUCN ranks were highly similar, with the EN species being the most evolutionarily distinct. EDGE, EDGE2, ED, and IUCN rankings were mostly consistent. All the LC species presented low values of EDGE and EDGE2, and the 12 threatened species have the highest EDGE and EDGE2

**TABLE 1** Results of EDGE analyses applied to *Chamaecrista* sect. *Chamaecrista* ser. *Coriaceae* species, organized from the highest EDGE (IUCN50) scores to the lowest (EDGE ranking). The records for each species, the IUCN Red List assessments (following criterion B), evolutionary distinctiveness (ED), global endangerment (GE), extinction risk (ER), EDGE, and EDGE2 are also listed per species.

EDGE ranking	EDGE2	ED ranking	Species	Records	ED	IUCN	GE	EDGE (ISAAC)	ER	EDGE (IUCN50)	EDGE2
1	1	1	<i>C. aristata</i>	17	5.967	EN	3	4.0206	0.42	0.9187	2.9674
2	2	2	<i>C. simplifacta</i>	16	5.168	EN	3	3.8988	0.42	0.775	2.1731
3	3	3	<i>C. burchellii</i>	15	3.005	EN	3	3.467	0.42	0.2328	1.0244
4	4	8	<i>C. cinerascens</i>	21	1.509	EN	3	2.9993	0.42	-0.4561	0.5706
5	5	9	<i>C. anceps</i>	3	1.461	EN	3	2.98	0.42	-0.4884	0.5638
5	5	9	<i>C. distichoclada</i>	13	1.461	EN	3	2.98	0.42	-0.4884	0.5638
7	9	13	<i>C. multinervia</i>	5	1.302	EN	3	2.9132	0.42	-0.6036	0.3745
8	7	15	<i>C. lagotois</i>	6	1.255	EN	3	2.8926	0.42	-0.6404	0.4730
8	7	16	<i>C. ulmea</i>	7	1.255	EN	3	2.8926	0.42	-0.6404	0.4730
10	11	6	<i>C. latifolia</i>	42	1.684	VU	2	2.3736	0.05	-2.4746	0.1878
10	11	6	<i>C. rossicorum</i>	34	1.684	VU	2	2.3736	0.05	-2.4746	0.1878
12	10	11	<i>C. olesiphylla</i>	44	1.446	VU	2	2.2807	0.05	-2.6269	0.2491
13	13	4	<i>C. tragacanthoides</i>	40	1.871	LC	0	1.0547	0.00005	-9.277	0.0734
14	14	5	<i>C. choriophylla</i>	20	1.711	LC	0	0.9973	0.00005	-9.3664	0.0652
15	15	11	<i>C. cardiostegia</i>	19	1.446	LC	0	0.8945	0.00005	-9.5347	0.0589
16	16	13	<i>C. mucronata</i>	32	1.302	LC	0	0.8338	0.00005	-9.6396	0.0570
17	17	17	<i>C. rotundata</i>	81	1.182	LC	0	0.7802	0.00005	-9.7363	0.0456
18	18	18	<i>C. arrojadoana</i>	103	0.788	LC	0	0.5811	0.00005	-10.1417	0.0222
18	18	18	<i>C. potentilla</i>	52	0.788	LC	0	0.5811	0.00005	-10.1417	0.0222

Note: EN = Endangered, LC = Least Concern, VU = Vulnerable.

values, occupying the first 12 places in the ranking. The last seven remaining places are filled with LC species, with a tie in the last position (*C. arrojadoana* (Harms) Rando and *C. potentilla* (Mart. ex Benth.) H. S. Irwin & Barneby). ED values ranged from 5.967 (*C. aristata* (Benth.) H. S. Irwin & Barneby) to 0.788 (*C. arrojadoana* and *C. potentilla*). *Chamaecrista aristata*, *C. simplifacta* H. S. Irwin & Barneby, and *C. burchellii* are placed in the first, second, and third positions in the EDGE, EDGE2, and ED rankings. When comparing the two different probability of extinction methods (ISAAC and IUCN50), we observed no difference in the EDGE ranking for the analyzed species. When comparing EDGE to EDGE2, although most of the ranks are the same, we found some differences: *C. multinervia* is switched with *C. lagotois* H. S. Irwin & Barneby and *C. ulmea* H. S. Irwin & Barneby, and *C. latifolia* and *C. rossicorum* are switched with *C. olesiphylla* (Table 1).

Regarding congruences between IUCN categories, EDGE, and EDGE2, species categorized as EN or VU and ranked highly for EDGE and EDGE2 are not restricted to a specific region of the campo rupestre (Figure 2). Although most of the threatened species occur in the Diamantina Plateau (region iii, see Figure 2), this is not the case for all

species, indicating no correlation between threat status and distribution among the endemism areas for the campo rupestre flora. For example, *C. rotundata* (Vogel) H. S. Irwin & Barneby, categorized as LC and ranked 17th for the EDGE and EDGE2 rankings (Table 1), is restricted to just one of the regions (iii, Diamantina Plateau; Figure 2), while *C. aristata* and *C. multinervia*, both EN and ranked first and seventh, respectively, for EDGE, and first and ninth for EDGE2, are each distributed across two regions (Grão Mogol and Diamantina Plateau regions for *C. aristata*, and Chapada Diamantina and Diamantina Plateau for *C. multinervia*). However, species like *C. simplifacta*, *C. burchellii*, and *C. ulmea*, all categorized as EN and ranked highly for EDGE and EDGE2 (Table 1), are each restricted to a single area (Diamantina Plateau, Chapada dos Veadeiros, and Grão Mogol, respectively; Figure 2). Thus, when analyzing the geographical distribution of species relative to their IUCN categories, one specific area of the campo rupestre environment does not host the most threatened species.

In the sensitivity analysis for *C. multinervia*'s imputation, altering the branch length does not affect the PD, EDGE, and EDGE2 diversity maps, or the residual maps for



each. However, altering the branch length changes the EDGE ranking (Appendix S4) because this leads to different ED values necessary for the EDGE calculation. Excluding *C. multinervia* has an impact on the diversity maps created for EDGE, EDGE2, and subsequent residuals, but not for PD and its residual (Appendix S3).

## DISCUSSION

This study compares three primary metrics used to factor evolutionary history into conservation prioritization: PD, EDGE, and EDGE2. Our study is the first to make this type of comparison and assess conservation priorities for the flora of Brazil using EDGE and EDGE2. Our results present the conservation status of 19 species in the *Chamaecrista* ser. *Coriaceae* and rank their conservation priority using the EDGE and EDGE2 metrics. Remarkably, endangered species are also the most evolutionarily distinct ones. We compared areas of high SR, PD, EDGE, and EDGE2 based on previously described areas of endemism in the region. Although these metrics are calculated differently, we recovered only small differences in their distribution across the campo rupestre. Based on our results, areas with the potential to be prioritized in the future are indicated and discussed below.

### Weighing threat categories and evolutionary distinctiveness

The newly reported IUCN categories for *Chamaecrista* ser. *Coriaceae* are broadly comparable to the threats faced by other plant lineages in the campo rupestre. According to PAN (Pougy et al., 2015a), out of 700 species assessed, about 256 species are threatened with extinction, categorized as CR, EN, and VU following the IUCN Red List. Here, we performed 17 new assessments and reassessed two species that were already included in PAN (*C. lagotois* and *C. aristata*), incorporating another 12 species in threatened categories in the southern Espinhaço Mountain Range alone. That means that of the 64 species of *Chamaecrista* described from the Diamantina Plateau (Cota et al., 2020), at least 15% (10 species of *Chamaecrista* sect. *Chamaecrista* ser. *Coriaceae* distributed there and assessed here) are assessed as threatened.

These findings were expected given the restricted species distributions in areas continuously impacted by habitat loss. However, different *Chamaecrista* species have distinct biological traits (e.g., Coutinho et al., 2015; Silva et al., 2017; Rando et al., 2019), and we still lack the fundamental ecological knowledge that could be significant for our analyses (e.g., unique subterranean systems, population data, reproductive biology; IUCN, 2022). Thus, it is important to acknowledge that the ER assessments we produced may not fully reflect the severity of the threats faced by these species and that they could be improved with more information in the future.

Another limitation is that some species do not reach maximum suitability in the ensemble SDMs, forcing us to use a low threshold for range binarization to include all species in the diversity maps. This could be due to the difficulty in modeling species distribution with a limited number of occurrence points (e.g., rare species) and species that can be considered specialists due to their adaptation to highly fragmented habitat types (Lomba et al., 2010).

Our study is the first to undertake this metric comparison for conservation prioritization in the campo rupestre and Brazil. The use of *Chamaecrista* ser. *Coriaceae* as a model group relies on the ecological and evolutionary importance of this group in the campo rupestre and the availability of the necessary data (e.g., taxonomic revision and time-calibrated phylogenetic tree). Having a complete phylogenetic tree is crucial for appropriate calculations of ED because this metric evaluates how isolated (i.e., distinct) a species is in the tree (Isaac et al., 2007; Molina-Venegas, 2021; Gumbs et al., 2023). Even though our sample size is small when considering the floristic diversity of the campo rupestre, *Chamaecrista* ser. *Coriaceae* follows the same pattern as other lineages in this ecosystem by having micro-endemic taxa associated with recent and fast radiations (e.g., *Paepalanthus* Mart. [Eriocaulaceae], *Cattleya* Lindl. [Orchidaceae], Lychnophorinae [Asteraceae], and others; Vasconcelos et al., 2020), facilitating its use as a model for studies investigating ecological and evolutionary process. *Chamaecrista* also has a high diversity of life forms and vegetative functional traits (de Souza et al., 2021), which is important for comparisons of lineages in the campo rupestre.

### Prioritizing conservation in the campo rupestre using EDGE and PD

Comparison of residual maps of PD, EDGE, and EDGE2 against SR reveals similarities and differences in the distribution of the three metrics (Figure 3). All metrics highlight the Grão Mogol area as a conservation priority, and the high residual EDGE and EDGE2 in this area is apparently driven by the distribution of *C. aristata*, ranked first for both metrics, and *C. ulmea*, ranked eighth and seventh, respectively (Figures 2 and 3). Grão Mogol is part of the southern Espinhaço Mountain Range, a highly fragmented area that tends to present smaller and more numerous endemism clusters, which may also result in higher speciation rates (Colli-Silva et al., 2019). In terms of floristic composition, Grão Mogol is considered more floristically similar to the Chapada Diamantina (Bitencourt and Rapini, 2013), an area of high endemism in the northern Espinhaço Mountain Range. Grão Mogol is among the areas of the Espinhaço Mountain Range with higher deforestation and large areas of planted eucalyptus (Ribas et al., 2016), besides other threats such as agriculture, mining, and livestock (Pougy et al., 2015b). These results are similar to those found in previous studies (Zappi et al., 2017; Cortez et al., 2021) and highlight the complexity of Grão Mogol in terms of natural history when compared to other campo rupestre areas, emphasizing the need for more studies

in this region. This area is partially protected by a park, the Parque Nacional de Grão Mogol, which is currently the only large protected area in the Grão Mogol region, essential for conserving its flora and fauna (Pougy et al., 2015b). Further studies should evaluate whether the species' survival can be assured by the current protected areas in the Grão Mogol region, for example, by contrasting whether areas of high suitability coincide with the current Conservation Units.

The distribution of PD differs from EDGE and EDGE2, especially in the northern Diamantina Plateau, where lower than expected PD and higher than expected EDGE and EDGE2 are observed. This discrepancy could be related to the fact that most of the species analyzed here occur in the Diamantina Plateau, and most are phylogenetically close to each other (Rando et al., 2019), decreasing PD values per species for each cell. In contrast, because the EDGE and EDGE2 values also consider a species' ER, these metrics effectively reflect the threats these species face (i.e., mining, fire, agriculture, livestock, human occupancy, and others; Pougy et al., 2015a) and give greater conservation importance to this area.

### Adequate metrics to conserve the evolutionary history of rapid and recent radiations

Regions with the highest SR are highlighted as the areas with the lowest PD, EDGE, and EDGE2 residuals. Other works found similar results for PD (e.g., Forest et al., 2007; Fritz and Rahbek, 2012), exhibiting that the simple correspondence of SR with PD can hide an important mismatch of biodiversity metrics. When comparing our results with other studies using the same EDGE methods (e.g., Forest et al., 2018; Hills et al., 2019), we observed that all species assessed here have relatively low EDGE values. The diversification of *Chamaecrista* ser. *Coriaceae* occurred recently, mainly during the Pleistocene (Rando et al., 2019; Vasconcelos et al., 2020), corresponding to relatively short terminal branch lengths and, consequently, low ED and EDGE values. This pattern can be extrapolated to other areas where lineages tend to be recent and tips have short terminal branches (e.g., the Andean Parámos; Madriñán et al., 2013). Thus, mountain chains can be particularly threatened as they are important areas for the emergence of new species and can be easily affected by even subtle changes in climate (Kohler et al., 2010; Bitencourt et al., 2016), which are predicted to become more extreme (Urban, 2015).

There are advantages and disadvantages in each metric we contrast here. In areas where life history and phylogenetic data are limited, such as the tropics (Vasconcelos, 2023), using PD can be advantageous in some cases. As described before, the EDGE calculations depend on the ED values, which require a complete phylogenetic tree for the focal group (i.e., a tree with all known species sampled; Molina-Venegas, 2021). However, this assumption is more flexible for PD, which focuses on the distance between tips in an area and not on a single value for each species (Faith, 1992). Thus, precise species delimitations

are less relevant, and synthetic phylogenies can be used for PD analyses (e.g., Li et al., 2019). However, this does not mean that evaluating individual species or collecting more accurate data should be neglected, but rather that in a scenario where rapid habitat loss and possible extinction are predicted, the use of PD for conservation prioritization is advantageous (Cowie et al., 2022). We briefly explore how data availability would affect conservation prioritization depending on PD or ED through a sensitivity analysis for the imputation of *C. multinervia*. Changes in the branch length of *C. multinervia* in the tree did not result in clear differences in diversity maps produced for PD, EDGE, and EDGE2, and subsequent residuals (Appendix S3), even though the ranking of species prioritization changed (Appendix S4). However, when we removed *C. multinervia* from the analysis, we observed differences in the EDGE, EDGE2, and their residuals maps, but not in the PD map and its residuals (Appendix S3).

Choosing between PD, EDGE, or EDGE2 also depends on the conservation approach. One of the most common strategies focuses on protecting areas prone to habitat loss, extrapolating this effort to the conservation of species there (Pimm and Raven, 2000). PD is a metric that evaluates the phylogenetic relatedness of species that co-occur in an area. In contrast, EDGE may represent the best of both worlds because it also includes ER assessments. Nevertheless, the lack of data on population dynamics and life-history traits for many tropical plants means that risk assessments tend to be preliminary in these areas (IUCN, 2022). The recently released EDGE2 method addresses these challenges by incorporating PD complementarity and phylogenetic uncertainty in its calculation and allowing species categorized as DD or NE to be included in the analysis (Gumbs et al., 2023).

An advantage of using EDGE instead of EDGE2 is that values for each species should be comparable among studies. EDGE2 values, in contrast, should be more sensitive to the phylogenetic scale used because they incorporate PD complementarity and ER assessments of closely related species in their calculations (Gumbs et al., 2023). Thus, values would not be comparable among studies that do not use the same phylogenetic tree, although the large proportion of EDGE2 scores is provided by branches near the tips, while deeper branches contribute relatively little (Gumbs et al., 2023). We observe that, in the case of our study, there was little difference between areas with high values of EDGE and EDGE2, potentially because both our focal area and taxonomic scale are relatively small.

### AUTHOR CONTRIBUTIONS

R.C.P., E.N.L., and T.V. conceived the idea of the study. R.C.P. and L.S.P. collected the data. J.G.R. performed taxonomic revision. R.C.P. and T.V. performed the analyses. R.C.P. and T.V. wrote the first draft, and all authors revised and approved the final version of the manuscript.

### ACKNOWLEDGMENTS

The authors thank the curators of the consulted herbaria; Mirian Antonicelli, Sandra Reinales, Jenifer Lopes, Addressa

Cabral, and Renato Magri for their support and discussions; Gwilym Lewis for discussion on Leguminosae; Matheus Cota for pictures; and Matheus Colli-Silva, Elton John de Lirio, and Justin Moat for discussion on methods. This work was supported by the Fundação de Amparo à Pesquisa do Estado de São Paulo (2018/24601-7, 2019/18627-6, 2018/02191-1, 2019/19544-7, and 2021/01573-0) and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (434692/2018-2).


## DATA AVAILABILITY STATEMENT

All scripts and data are available at [https://github.com/rpizzardo/conservation\\_chamaecrista.git](https://github.com/rpizzardo/conservation_chamaecrista.git).

## ORCID

Raquel C. Pizzardo  <http://orcid.org/0000-0002-5122-9994>

Eimear Nic Lughadha  <http://orcid.org/0000-0002-8806-4345>

Juliana Gastaldello Rando  <http://orcid.org/0000-0002-3714-8231>

Félix Forest  <http://orcid.org/0000-0002-2004-433X>

Anselmo Nogueira  <http://orcid.org/0000-0002-8232-4636>

Luana S. Prochazka  <http://orcid.org/0000-0002-7443-3963>

Thais Vasconcelos  <http://orcid.org/0000-0001-9991-7924>

## REFERENCES

- Allen, G. R. 2008. Conservation hotspots of biodiversity and endemism for Indo-Pacific coral reef fishes. *Aquatic Conservation: Marine and Freshwater Ecosystems* 18(5): 541–556.
- Allouche, O., A. Tsoar, and R. Kadmon. 2006. Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). *Journal of Applied Ecology* 43: 1223–1232.
- Antonelli, A., C. Fry, R. J. Smith, M. S. J. Simmonds, P. J. Kersey, H. W. Pritchard, M. S. Abbo, et al. 2020. State of the World's Plants and Fungi 2020. Royal Botanic Gardens, Kew, Richmond, United Kingdom.
- BFG (Brazil Flora Group). 2021. Coleção Flora do Brasil 2020. Jardim Botânico do Rio de Janeiro, Rio de Janeiro, Brazil.
- Bitencourt, C., and A. Rapini. 2013. Centres of endemism in the Espinhaço Range: Identifying cradles and museums of Asclepiadoideae (Apocynaceae). *Systematics and Biodiversity* 11(4): 525–536.
- Bitencourt, C., A. Rapini, L. S. Damascena, and P. M. Junior. 2016. The worrying future of the endemic flora of a tropical mountain range under climate change. *Flora* 218: 1–10.
- Butchart, S. H. M., M. Walpole, B. Collen, A. van Strien, J. P. W. Scharlemann, R. E. A. Almond, J. E. M. Baillie, et al. 2010. Global biodiversity: Indicators of recent declines. *Science* 328(5982): 1164–1168.
- Cartwright, J. 2019. Ecological islands: Conserving biodiversity hotspots in a changing climate. *Frontiers in Ecology and the Environment* 17(6): 331–340.
- Colli-Silva, M., T. N. C. Vasconcelos, and J. R. Pirani. 2019. Outstanding plant endemism levels strongly support the recognition of *campo rupestre* provinces in mountaintops of eastern South America. *Journal of Biogeography* 46(8): 1723–1733.
- Conceição, A. S., L. P. Queiroz, G. P. Lewis, M. J. G. Andrade, P. R. M. Almeida, A. S. Schnadelbach, and C. van den Berg. 2009. Phylogeny of *Chamaecrista* Moench (Leguminosae-Caesalpinioideae) based on nuclear and chloroplast DNA regions. *Taxon* 58: 1168–1180.
- Conceição, A. A., A. Rapini, F. F. do Carmo, J. C. Brito, G. A. Silva, S. P. S. Neves, and C. M. Jacobi. 2016. Rupestrian grassland vegetation, diversity, and origin. In G. W. Fernandes [ed.], Ecology and conservation of mountaintop grasslands in Brazil. Springer, Cham, Switzerland.
- Cortez, M. B. de S., R. A. Folk, C. J. Grady, J. P. Spoelhof, S. Smith, D. E. Soltis, and P. S. Soltis. 2021. Is the age of plant communities predicted by the age, stability and soil composition of the underlying landscapes? An investigation of OCBILs. *Biological Journal of the Linnean Society* 133(2): 297–316.
- Cota, M. M. T., J. G. Rando, and R. Mello-Silva. 2020. *Chamaecrista* (Leguminosae) of the Diamantina Plateau, Minas Gerais, Brazil, with six new species and taxonomic novelties. *Phytotaxa* 469(1): 1–82.
- Coutinho, I. A. C., D. M. T. Francino, and R. M. S. A. Meria. 2015. New records of colleters in *Chamaecrista* (Leguminosae, Caesalpinioideae s.l.): Structural diversity, secretion, functional role, and taxonomic importance. *International Journal of Plant Sciences* 176(1): 72–85.
- Cowie, R. H., P. Bouchet, and B. Fontaine. 2022. The sixth mass extinction: Fact, fiction or speculation? *Biological Reviews* 9: 640–663.
- de Souza, A. O., G. P. Lewis, and M. J. da Silva. 2021. A new infrageneric classification of the pantropical genus *Chamaecrista* (Fabaceae: Caesalpinioideae) based on a comprehensive molecular phylogenetic analysis and morphology. *Botanical Journal of the Linnean Society* 197(3): 350–395.
- Echternacht, L., M. Trovó, C. T. Oliveira, and J. R. Pirani. 2011. Areas of endemism in the Espinhaço range in Minas Gerais, Brazil. *Flora-Morphology, Distribution, Functional Ecology of Plants* 206(9): 782–791.
- Faith, D. P. 1992. Conservation evaluation and phylogenetic diversity. *Biological Conservation* 61: 1–10.
- Forest, F., R. Grenyer, M. Rouget, T. J. Davies, R. M. Cowling, D. P. Faith, A. Balmford, et al. 2007. Preserving the evolutionary potential of floras in biodiversity hotspots. *Nature* 445: 757–760.
- Forest, F., J. Moat, E. Baloch, N. A. Brummitt, S. P. Bachman, S. Ickert-Bond, P. Hollingsworth, et al. 2018. Gymnosperms on the EDGE. *Scientific Reports* 8: 6053.
- Fritz, S. A., and C. Rahbek. 2012. Global patterns of amphibian phylogenetic diversity. *Journal of Biogeography* 38: 1373–1382.
- Giulietti, A. M., and J. R. Pirani. 1988. Patterns of geographic distribution of some plant species from the Espinhaço Range, Minas Gerais and Bahia, Brazil. In Proceedings of a Workshop on Neotropical Distribution Patterns, May 2015. Academia Brasileira de Ciências, Rio de Janeiro, Brazil.
- Giulietti, A. M., and J. R. Pirani. 1997. Espinhaço range region, eastern Brazil. In Centres of plant diversity: A guide and strategy for their conservation, Vol. 3, the Americas. Worldwide Fund for Nature and International Union for Conservation of Nature, Cambridge, United Kingdom.
- Gumbs, R., C. L. Gray, M. Böhm, I. J. Burfield, O. R. Couchman, D. P. Faith, F. Forest, et al. 2023. The EDGE2 protocol: Advancing the prioritisation of Evolutionarily Distinct and Globally Endangered species for practical conservation action. *PLoS Biology* 21(2): e3001991.
- Hills, R., S. Bachman, F. Forest, J. Moat, and P. Wilkin. 2019. Incorporating evolutionary history into conservation assessments of a highly threatened group of species, South African *Dioscorea* (Dioscoreaceae). *South African Journal of Botany* 123: 296–307.
- Humphreys, A. M., R. Govaerts, S. Z. Ficinski, E. Nic Lughadha, and M. S. Vorontsova. 2019. Global dataset shows geography and life form predict modern plant extinction and rediscovery. *Nature Ecology and Evolution* 3(7): 1043–1047.
- Inglis, P. W., and T. B. Cavalanti. 2018. A molecular phylogeny of the genus *Diplusodon* (Lythraceae), endemic to the *campos rupestres* and cerrados of South America. *Taxon* 67(1): 66–82.
- Irwin, H. S., and R. C. Barneby. 1978. Monographic studies in *CassiaAbsusGrimaldia* (Leguminosae Caesalpinioideae). III. Sections *Absus* and *Grimaldia*. Memoirs of the New York Botanical Garden, vol. 30. New York Botanical Garden, Bronx, New York, USA.
- Irwin, H. S., and R. C. Barneby. 1982. The American Cassiinae: A synoptical revision of Leguminosae tribe Cassieae subtribe Cassiinae in the New World. *Memoirs of the New York Botanical Garden*, 35, 455–918. New York Botanical Garden, Bronx, New York, USA.



- Isaac, N. J. B., and W. D. Pearse. 2018. The use of EDGE (Evolutionary Distinct Globally Endangered) and EDGE-like metrics to evaluate taxa for conservation. In R. Scherson and D. Faith [eds.], *Phylogenetic diversity*. Springer, Cham, Switzerland.
- Isaac, N. J. B., S. T. Turvey, B. Collen, C. Waterman, and J. E. M. Baillie. 2007. Mammals on the EDGE: Conservation priorities based on threat and phylogeny. *PLoS ONE* 2(3): e296.
- Isaac, N. J. B., D. W. Redding, H. M. Meredith, and K. Safi. 2012. Phylogenetically-informed priorities for amphibian conservation. *PLoS ONE* 7(8): e43912.
- IUCN. 2022. The IUCN Red List of Threatened Species [online]. Website: <https://www.iucnredlist.org> [accessed 25 May 2021].
- IUCN Standards and Petitions Committee. 2022. Guidelines for Using the IUCN Red List Categories and Criteria. Version 15.1. Prepared by the Standards and Petitions Committee. IUCN, Gland, Switzerland.
- Karger, D. N., O. Conrad, J. Böhrer, T. Kawohl, H. Kreft, R. W. Soria-Auza, N. E. Zimmermann, et al. 2017. Climatologies at high resolution for the earth's land surface areas. *Scientific Data* 4: 170122.
- Kembel, S. W., P. D. Cowan, M. R. Helmus, W. K. Cornwell, H. Morlon, D. D. Ackerly, S. P. Blomberg, and C. O. Webb. 2010. Picante: R tools for integrating phylogenies and ecology. *Bioinformatics Applications Note* 26(11): 1463–1464.
- Kling, M. M., B. D. Mishler, A. H. Thornhill, B. G. Baldwin, and D. D. Ackerly. 2018. Facets of phylodiversity: Evolutionary diversification, divergence and survival as conservation targets. *Philosophical Transactions of the Royal Society B* 374: 20170397.
- Kohler, T., M. Giger, H. Hurni, C. Ott, U. Wiesmann, S. W. von Dach, and D. Maselli. 2010. Mountains and climate change: A global concern. *Mountain Research and Development* 30(1): 53–55.
- Li, J., S. W. Gale, P. Kumar, J. Zhang, and G. A. Fischer. 2018. Prioritizing the orchids of a biodiversity hotspot for conservation based on phylogenetic history and extinction risk. *Botanical Journal of the Linnean Society* 186(4): 473–497.
- Li, D., L. Trotta, H. E. Marx, J. M. Allen, M. Sun, D. E. Soltis, P. S. Soltis, et al. 2019. For common community phylogenetic analyses, go ahead and use synthesis phylogenies. *Ecology* 100(9): e02788.
- Lomba, A., L. Pellissier, C. Randin, J. Vicente, F. Moreira, J. Honrado, and A. Guisan. 2010. Overcoming the rare species modelling paradox: A novel hierarchical framework applied to an Iberian endemic plant. *Biological Conservation* 143(11): 2647–2657.
- Mace, G. M., J. L. Gittleman, and A. Purvis. 2003. Preserving the tree of life. *Science* 300(5626): 1707–1709.
- Madriñán, S., A. J. Cortés, and J. E. Richardson. 2013. Páramo is the world's fastest evolving and coolest biodiversity hotspot. *Frontiers in Genetics* 4: 192.
- Molina-Venegas, R. 2021. Conserving evolutionarily distinct species is critical to safeguard human well-being. *Scientific Reports* 11: 24187.
- Mooers, A. Ø., D. P. Faith, and W. P. Maddison. 2008. Converting endangered species categories to probabilities of extinction for phylogenetic conservation prioritization. *PLoS ONE* 3(11): e3700.
- Moro, M. F., I. A. Silva, F. S. de Araújo, E. N. Lughadha, T. R. Meagher, and F. R. Martins. 2015. The role of edaphic environment and climate in structuring phylogenetic pattern in seasonally dry tropical plant communities. *PLoS ONE* 10(3): e0119166.
- Myers, N., R. A. Mittermeier, C. G. Mittermeier, G. A. B. Fonseca, and J. Kent. 2000. Biodiversity hotspots for conservation priorities. *Nature* 403: 853–858.
- Naimi, B., N. A. S. Hamm, T. A. Groen, A. K. Skidmore, and A. G. Toxopeus. 2014. Where is positional uncertainty a problem for species distribution modelling. *Ecography* 37: 191–203.
- Naimi, B., and M. B. Araújo. 2016. sdm: A reproducible and extensible R platform for species distribution modelling. *Ecography* 39: 368–375.
- Nic Lughadha, E., S. P. Bachman, T. C. C. Leão, F. Forest, J. M. Halley, J. Moat, C. Aceedo, et al. 2020. Extinction risk and threat to plants and fungi. *Plants, People and Planet* 2: 389–408.
- Orme, C. D. L., R. Davies, M. Burgess, F. Eigenbrod, N. Pickup, V. A. Olso, A. J. Webster, et al. 2005. Global hotspots of species richness are not congruent with endemism or threat. *Nature* 436: 1016–1019.
- Pacífico, R., F. Almeda, A. Frota, and K. Fidanza. 2020. Areas of endemism on Brazilian mountaintops revealed by taxonomically verified records of Microlicieae (Melastomataceae). *Phytotaxa* 450(2): 119–148.
- Peterson, A. T., J. Soberón, R. G. Pearson, R. P. Anderson, E. Martínez-Meyer, M. Nakamura, and M. B. Araújo. 2011. *Ecological niches and geographic distributions*. Princeton University Press, Princeton, New Jersey, USA.
- Phillips, S. J., R. P. Anderson, and R. E. Schapire. 2006. Maximum entropy modeling of species geographic distributions. *Ecological Modelling* 190(3–4): 231–259.
- Pimm, S. L., and P. Raven. 2000. Extinction by numbers. *Nature* 403: 843–845.
- Pimm, S. L., M. Ayres, A. Balmford, G. Branch, K. Brandon, T. Brooks, R. Bustamante, et al. 2001. Can we defy nature's end? *Science* 293(5538): 2207–2208.
- Pougy, N., M. Verdi, E. Martins, R. Loyola, and G. Martinelli. 2015a. Plano de Ação Nacional para a conservação da flora ameaçada de extinção da Serra do Espinhaço Meridional. CNCFlora, Jardim Botânico do Rio de Janeiro, Laboratório de Biogeografia da Conservação, Rio de Janeiro, Brazil.
- Pougy, N., M. Verdi, E. Martins, D. Maurenza, R. Loyola, and G. Martinelli. 2015b. Plano de Ação Nacional para a conservação da flora ameaçada de extinção da região de Grão Mogol-Francisco Sá. CNCFlora, Jardim Botânico do Rio de Janeiro, Laboratório de Biogeografia da Conservação, Rio de Janeiro, Brazil.
- R Core Team. 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
- Rando, J. G., A. R. Zuntini, A. S. Conceição, C. van den Berg, J. R. Pirani, and L. P. de Queiroz. 2016. Phylogeny of *Chamaecrista* ser. *Coriaceae* (Leguminosae) unveils a lineage recently diversified in Brazilian campo rupestre vegetation. *International Journal of Plant Sciences* 177(1): 3–17.
- Rando, J. G., J. R. Pirani, M. M. T. Cota, and G. P. Lewis. 2019. New circumscription, morphology and synopsis of *Chamaecrista* sect. *Chamaecrista* ser. *Coriaceae* (Leguminosae). *Brittonia* 71(30): 268–298.
- Rando, J. G., M. M. T. Cota, A. S. Conceição, A. R. Barbosa, and T. L. A. Barros. 2020. *Chamaecrista* in Flora do Brasil 2020 [online]. Website: <http://floradobrasil.jbrj.gov.br/reflora/floradobrasil/FB22876> [accessed 16 September 2021].
- Rapini, A., P. L. Ribeiro, S. Lambert, and J. R. Pirani. 2008. A flora dos campos rupestres da Cadeia do Espinhaço. *Megadiversidade* 4: 15–23.
- Raven, P. H., R. Y. Gereau, P. B. Phillipson, C. E. Chatelan, C. N. Jenkins, and C. U. Ulloa. 2020. The distribution of biodiversity richness in the tropics. *Science Advances* 6(37): EABC6228.
- Revell, L. J. 2023. phytools: An R package for phylogenetic comparative biology (and other things). *Methods in Ecology and Evolution* 3: 217–223.
- Ribas, R. P., R. M. Caetano, B. M. Gontijo, and J. H. de A. Xavier. 2016. Afforestation in the rupestrian grasslands: The augmenting pressure of *Eucalyptus*. In G. W. Fernandes [ed.], *Ecology and conservation of mountaintop grasslands in Brazil*. Springer, Cham, Switzerland.
- Silva, M. dos S., I. A. C. Coutinho, M. N. Araújo, and R. M. S. A. Meira. 2017. Colleters in *Chamaecrista* (L.) Moench sect. *Chamaecrista* and sect. *Caliciopsis* (Leguminosae-Caesalpinioideae): Anatomy and taxonomic implications. *Acta Botanica Brasilica* 31(3): 382–391.
- Silveira, F. A. O., D. Negreiros, N. P. U. Barbosa, E. Buisson, F. F. Carmo, D. W. Carstensen, A. A. Conceição, et al. 2016. Ecology and evolution of plant diversity in the endangered *campo rupestre*: A neglected conservation priority. *Plant and Soil* 403: 129–152.
- Stewart, J. R., A. W. Lister, I. Barnes, and L. Dalén. 2010. Refugia revisited: Individualistic responses of species in space and time. *Proceedings of the Royal Society B: Biological Sciences* 277: 661–671.
- Ulloa, C. U., P. Acevedo-Rodriguez, S. Beck, M. J. Belgrano, R. Bernal, P. E. Berry, L. Brako, et al. 2017. An integrated assessment of vascular plant species of the Americas. *Science* 358(6370): 1614–1617.
- Urban, M. C. 2015. Accelerating extinction risk from climate change. *Science* 348(6234): 571–573.

- Vasconcelos, T. 2023. A trait-based approach to determining principles of plant biogeography. *American Journal of Botany* 110(2): e16127.
- Vasconcelos, T. N. C., S. Alcantara, C. O. Andrino, F. Forest, M. Reginato, M. F. Simon, and J. R. Pirani. 2020. Fast diversification through a mosaic of evolutionary histories characterizes the endemic flora of ancient Neotropical mountains. *Proceedings of the Royal Society B: Biological Sciences* 287: 20192933.
- Wilson, K. A., M. F. McBride, M. Bode, and H. P. Possingham. 2006. Prioritizing global conservation efforts. *Nature* 440(7082): 337–340.
- Yessoufou, K., B. H. Daru, R. Tafirei, H. O. Elansary, and I. Ramped. 2017. Integrating biogeography, threat and evolutionary data to explore extinction crisis in the taxonomic group of cycads. *Ecology and Evolution* 7(8): 2735–2746.
- Zappi, D. C., E. Lucas, B. L. Stannard, E. N. Lughadha, J. R. Pirani, L. P. de Queiroz, S. Atkins, et al. 2003. Lista de plantas vasculares de Catolés, Chapada Diamantina, Bahia, Brasil. *Boletim de Botânica da Universidade de São Paulo* 21(2): 345–398.
- Zappi, D. C., M. F. Moro, T. R. Meagher, and E. Nic Lughadha. 2017. Plant biodiversity drivers in Brazilian *campos rupestres*: Insights from phylogenetic structure. *Frontiers in Plant Science* 8: 2141.

## SUPPORTING INFORMATION

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

**Appendix S1.** Distribution points of *Chamaecrista* ser. *Coriaceae*.

**Appendix S2.** Map showing an overview of the threats used in the IUCN Red List assessment.

**Appendix S3.** Sensitivity analysis for *Chamaecrista multinervia* imputation and species distribution modeling presence and absence threshold.

**Appendix S4.** Tables with ranking and diversity indices values for different *Chamaecrista multinervia* imputations. Species are ordered by higher to lower values of EDGE\_IUCN.

**Appendix S5.** Evolutionary distinctiveness (ED) and extinction risk (ER) maps and associated residuals.

**How to cite this article:** Pizzardo, R. C., E. Nic Lughadha, J. G. Rando, F. Forest, A. Nogueira, L. S. Prochazka, B. E. Walker, and T. Vasconcelos. 2024. An assessment of methods to combine evolutionary history and conservation: A case study in the Brazilian campo rupestre. *Applications in Plant Sciences* 12(3): e11587.  
<https://doi.org/10.1002/aps3.11587>