The future scenario of an iconic tree from the Brazilian Cerrado: perspectives on *Eremanthus* Less. (Asteraceae) conservation

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Abstract
Characterized as one of the largest biodiversity hot spots, the Cerrado ecoregion is home to a wide variety of endemic species. Several threats such as agricultural expansion and habitat fragmentation put the species of the Cerrado ecosystems and biodiversity at risk. Thus, this study analysed the genus *Eremanthus*, which has abundant species in the Cerrado and suffers from intense anthropogenic pressure due to overexploitation, mainly as a material utilized for the construction of fences and the extraction of essential oils. Environmental suitability was estimated for the genus for the present and future (2070), in order to characterize the importance of the climate in the species distribution and to analyse the conservation status of the genus. The Species Distribution Modelling and Gap Analysis showed that the areas of environmental suitability are limited and are found in a matrix composed of a high presence of anthropic activity, which can intensify the loss of species habitat and increase the vulnerability of the group. The studied species were classified as Endangered and Vulnerable according to IUCN criteria, presenting very reduced areas of environmental suitability projected in the future and a low percentage of species in protected areas, that may influence possible species extinctions in the genus. Thus, this study provides insights to assist in conservation planning and reinforces the importance of protecting the biodiversity of the Cerrado.

Keywords *Campos rupestres* · Environmental suitability · Espinhaço range · Occupancy · Occurrence · Threatened species

1 Introduction
The Cerrado is the largest neotropical savannah, occupying central Brazil, part of Bolivia and Paraguay, with a biogeographical and morpho-climatic domain extending over approximately 2 million km². It is widely recognized as one of the largest biodiversity hot spots in the world due to its high species richness and index of endemism, with 44% of the total plant species and 80% of its woody plants exclusive to this environment (Lenthall et al. 1999; Klink and Machado 2005). The high environmental heterogeneity of the Cerrado favours the floristic diversity of plant communities, especially through the variety of soils (latosols, cambisols, gleys, hydromorphic laterite, litholic, quartzitic sands, podzolic oxisols), climates and geomorphologies (Siqueira and Durigan 2007; Souza-Neto et al. 2016).

In the face of this environmental distinctiveness and despite this phytophysionomy being considered an important biodiversity hot spot (Silveira et al. 2016, 2020), the Cerrado suffers from intense environmental degradation. Currently, less than 20% of its native vegetation is protected within reserves, with an estimated loss of 46% of native vegetation; land use projections foresee intense deforestation in the coming decades (Strassburg et al. 2017; Terra et al. 2017). Environmental protection areas correspond to 6.5% of the Cerrado and only 3% of the natural vegetation is included in strictly protected areas in IUCN categories I to III (Françoso et al. 2015). Therefore, there is an urgent need to preserve the biodiversity of the Cerrado and scientific research towards this goal has in the last two decades contributed to: the identification of biogeographic districts, the assessment of land use and protected areas, spatial–temporal analyses of deforestation, climate studies, studies of the effects of fire on biodiversity dynamics, surveys of threats...
and proposals to control them (Guisan et al. 2013; Françoso et al. 2015; Velazco et al. 2019; Colli et al. 2020; Fernandes et al. 2020).

Some of this research asserts that the main threats to the Cerrado biodiversity are uncontrolled agricultural expansion causing deforestation, habitat fragmentation and pollution of waterbodies with fertilizers and lime, intentional burning and replacement of Cerrado vegetation by exotic grasses for the establishment of cattle pastures that interfere with the natural ecosystem cycle (Klink and Machado 2005; Scarano et al. 2014) (Fig. 1). Consequently, several taxonomic groups (e.g., angiosperms, mammals and birds) are more likely to disappear from the natural environment, presenting drastic shrinkage of ecological niche over the years (Marco et al. 2018; Borges et al. 2019; Angulo et al. 2021).

One of these threatened groups is *Eremanthus* (Asteraceae, Vernonieae), a neotropical genus of treelets or rarely shrubs, distributed almost exclusively in the Cerrado, with an important presence in the Espinhaço Range, which harbours many endemic species (MacLeish 1987; Loeuille et al. 2019; Alves and Loeuille 2021). The species of the genus are easily recognizable and generally occur in large populations, being commonly known as “candeias” (loosely translated as lamps) due to their use as fuel (Scolforo et al. 2002; Macedo et al. 2020). However, the use of wood from *Eremanthus* species as a fuel source is not the sole reason why their species suffer intense anthropogenic overexploitation.

*Eremanthus* species, mainly *E. erythropappus* and *E. incanus*, are under constant threat due to their use as fence posts and processes of essential oil extraction by industries (Scolforo et al. 2002; Pádua et al. 2016). The main component of these essential oils is α-bisabolol, also known as levomenol, a monocyclic sesquiterpene alcohol, firstly isolated from chamomile (*Matricaria chamomilla* L.) in 1951. It has anti-allergic, antibacterial, antiphlogistic, anti-irritant, antymycotic, dermatological, antispasmodic and vermifugal properties, being widely used in the cosmetics and pharmaceutical industry.

The situation described above can be exemplified by *Eremanthus erythropappus*, an important example within the genus, presenting studies regarding its conservation situation and seeking solutions to control the

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Fig. 1  
(a) Large deforested area where a population of *E. rondoniensis* was present at least until 2004;  
(b) The wood of *E. capitatus*;  
(c) *E. incanus*;  
(d) *E. elaeagnus*;  
(e) *E. erythropappus* being used for the construction of a bridge.
overexploitation of the species (Araújo et al. 2018; Pádua et al. 2021). Some studies propose a focus on the genetic conservation of species through vegetative propagation methods, maintaining selected genotypes (Fonseca et al. 2021). However, it is important to consider that population distribution analyses show that over short distances, populations are genetically similar and genetic assessments in species populations under anthropogenic influence help to identify priority conservation areas (Pádua et al. 2021). Therefore, a possible solution to better understand the effectiveness of conservation approaches is integrating different methodologies into conservation assessments (Peterson 2011; Grossi et al. 2017; Neves et al. 2018).

A commonly used methodology is the assessment of species threat level and some Eremanthus species are indeed included in endangered species lists. One of the most widely used threatened species classification systems is the International Union for Conservation of Nature (IUCN) Red List, presenting categories and criteria that allow an objective evaluation of species extinction risk (IUCN Standards and Petitions Committee 2019). The two most frequently used metrics for assessing species according to the IUCN specifications are the Extent of Occurrence (EOO) and Area of Occupancy (AOO), with many studies using a variety of Species Distribution Modelling (SDM) methods, useful for the identification of areas of environmental suitability, in order to calculate EOO and AOO (Marcer et al. 2013; Fivaz and Gonseth 2014; Syfert et al. 2016; Breiner et al. 2017; Marco et al. 2018; Kaky and Gilbert 2019; Moat et al. 2019), especially in cases where data are scarce.

Considering these aspects and the importance of the genus, this study aims to assess the conservation of all Eremanthus species through the construction of environmental distribution models, application of the IUCN criteria based on records and SDM, identification of protected areas (PAs) in the distribution model areas and areas with lack of conservation through the Gap Analysis (GA). We include campos rupestres within the Cerrado in order to remain consistent with methodological approaches. Therefore, the main questions we intend to answer are: (1) What are the estimated projected environmental suitability areas for the species over time (present and future)? (2) Is there a change in environmental suitability between present and future estimates? (3) What proportion of the species are included in conservation units? (4) What is the extinction risk classification for the species according to the IUCN criteria? (5) What is the future of species conservation in the face of threats linked to environmental suitability reduction?

## 2 Materials and methods

**Data acquisition** – The initial step was to obtain georeferenced data from all species of Eremanthus and create a database. Most of the information was obtained from a personal database, which contains high-quality taxonomic identification data, with the support of additional records stored in the Species Link (http://splink.cria.org.br) and Global Biodiversity Information Facility (GBIF—https://www.gbif.org) online databases. After the compilation, the Eremanthus database was edited to remove unreliable records, keeping only data suitable for use in research, eliminating problems with misidentification, inaccuracy, records outside raster boundaries, more than one datapoint per pixel and duplicated records (Giannini et al. 2012). This process was carried out manually and with the clean functions (“clean_dupl”, “clean_nas”, “clean_uni”) of the “modleR” 0.0.0.9000 (Sánchez-Tapia et al. 2018) package in RStudio 1.3.1056 (RStudio Team 2020) with R 3.6.3 (R Core Team 2020), in a two-stage (automatic and manual) cleaning process (Panter et al. 2020). Only 15 species (E. capitatus (Fig. 1b), E. cinctus, E. crotonoides, E. elaeagnus (Fig. 1d), E. erythropappus, E. glomerulatus, E. goyazensis, E. incanus (Fig. 1c), E. mattogrossensis, E. mollis, E. polycetalphus, E. reticulatus, E. rondoniensis, E. synecephalus, E. uniflorus) were included in this study, because the other nine species (E. arboreus (Gardner) MacLeish, E. argenteus MacLeish & H.Schumach., E. auriculatus MacLeish & H.Schumach., E. brevifolius Loeuille, E. hatschbachii H.Rob., E. ovatifolius Loeuille & Pirani, E. praeterrissis Loeuille & Pirani, E. tomentosus Loeuille & Bringel, E. veadeiroensis H.Rob.) have less than 10 records in the database. A complete list of the studied species and the environment where they occur is available in Table 1.

**Species distribution modelling** – SDM was performed using the “modleR” package in RStudio. Brazil was the main study area, except for E. cinctus, E. mattogrossensis and E. rondoniensis, for which Brazil and Bolivia were used as base area as there was a suspicion from preliminary modelling tests that an area of suitability for E. cinctus could be present in Bolivia and additionally because the other two species occur in both countries. Nineteen bioclimatic variables were obtained from the WorldClim version 1.4 database (Hijmans et al. 2005) with 2.5 min spatial resolution. The Global Climate Model (GCM) used was the Model for Interdisciplinary Research on Climate-Earth System Model (MIROC-ESM). To apply in the analysis, these variables were cropped through the “raster” package in RStudio using the previously described study area as the base (Hijmans 2021).

The selection of the bioclimatic variables for modelling was performed with the “modleR” package. Correlated
variables were excluded, maintaining the bioclimatic variables Mean Diurnal Range (Mean of monthly (max temp–min temp)), Isothermality, Mean Temperature of Wettest Quarter, Mean Temperature of Warmest Quarter, Precipitation of Wettest Month, Precipitation Seasonality (Coefficient of Variation), Precipitation of Wettest Quarter and Precipitation of Coldest Quarter. The modelling was carried out for the present (1960–1990) and projected to the future in 2070 with all Representative Concentration Pathways (RCPs) scenarios (2.6, 4.5, 6.0 and 8.5), to visualize the range of suitable areas for species occupation through time. To maintain consistency with other analyses and avoid confusion, RCP 8.5 was maintained as a reference in the presentation of results and discussion. Maxent and Bioclim were the algorithms used for modelling and the models used in this study are an ensemble of both, based on models with True Skill Statistics (TSS) value above 0.7.

**IUCN Red List Assessment** – The recommendations in the Guidelines for Application of IUCN Red List Categories and Criteria version 3.1 (IUCN 2001, 2012) and Guidelines for Application of IUCN Red List Categories and Criteria version 14 (IUCN Standards and Petitions Committee 2019) demonstrate how to carry out EOO and AOO calculations, including cases of spatially predicted sites. It is important to highlight that the use of SDM in conservation status assessments needs to consider the Minimum Convex Polygon (MCP), which encompasses all the predicted habitat areas to estimate EOO, and a grid size of 2 × 2 km to estimate AOO (IUCN Standards and Petitions Committee 2019). Furthermore, SDM models need to be binarized through a threshold value before these calculations. The thresholds must be properly established because they directly affect the coverage of suitable habitats in the binarized models and, consequently, the species status assessment (Liu et al. 2005, 2016).

The species classification method for IUCN red-listing followed the parameters established by the IUCN Red List Categories and Criteria version 3.1 (IUCN 2001, 2012) and Guidelines for Application of IUCN Red List Categories and Criteria version 14 (IUCN Standards and Petitions Committee 2019). The species were submitted to criterion B, which refers to the limitation of geographic distribution, and to subcriterion (b), referring to continuous decline. No analyses were carried out to enable the classification of species in subcriteria (a) and (c), which deal with severely fragmented populations and extreme fluctuations in populations, respectively. According to the IUCN provisions, to determine that a species is fully classified in criterion B, the assessed species must also meet the requirements of at least two of the three previously mentioned subcriteria. Therefore, the results of the assessment of *Eremanthus* species based on the IUCN criteria are presented in a preliminary way. Nevertheless, in the face of worsening imminent environmental threats worldwide, this study presents consistent and important preliminary results that will serve as basis for a classification that completely fulfils the IUCN Red List requirements.

The letters “f”, “h”, “l”, “p”, “r” and “t”, when mentioned together with EOO and AOO, are abbreviations for “future”, “hull” (referring to convex hull/MCP), “loss”, “present”, “records” and “total” (referring to total area), respectively. To evaluate *Eremanthus* species according to the IUCN specifications for criterion B, individual records were used to calculate EOOr (criterion B1), through MCP, and AOOr (criterion B2), using the 2 × 2 km (4 km²) reference scale for grid size. EOO and AOO of SDM models of the present

| Species | Environment |
|---------|-------------|
| *E. capitatus* (Spreng.) MacLeish | Cerrado, campos Rupestres, restinga and secondary forests |
| *E. cinctus* Baker | Cerrado |
| *E. crotonoides* Sch.Bip | Cerrado, campos rupestres, secondary woods and gallery forest |
| *E. elaeagnus* Sch.Bip | Cerrado and campos rupestres |
| *E. erythropappus* (DC.) MacLeish | Cerrado, campos rupestres and secondary forests |
| *E. glomerulatus* Less | Cerrado and campos rupestres |
| *E. goyazensis* Sch.Bip | Cerrado and campos rupestres |
| *E. incanus* Less | Cerrado, campos rupestres, secondary forests and caatinga |
| *E. mattogrossensis* Kuntze | Cerrado and campos rupestres |
| *E. mollis* Sch.Bip | Cerrado and campos rupestres |
| *E. polycephyalus* (DC.) MacLeish | Campos rupestres |
| *E. reticulatus* (Gardner) Loeuille, Semir & Pirani | Cerrado |
| *E. rondoniensis* MacLeish & H.Schumach | Campos rupestres |
| *E. syncephalus* (Sch.Bip.) Loeuille, Semir & Pirani | Cerrado |
| *E. uniflorus* MacLeish & H.Schumach | Cerrado and campos rupestres |
(EOOp and AOOp) and of the future with RCP 8.5 (EOOf and AOOf) were calculated, as well as their respective values within the MCP (EOOp, AOOp, EOOf, AOOf), in order to identify a possible decline of a species in the projections. To perform such calculations, SDM models were binarized (i.e., areas with environmental suitability received a value of 1 and areas without environmental suitability received a 0 value) by obtaining the threshold values when the Minimal Predicted Area (MPA) with 90% of the species records was applied, in order to avoid any possible remaining incorrect records and ensure the reliability of the records in the analysis. With these binary models representing the potential habitat area, the area of occupied habitat was estimated and EOOp, AOOp, EOOf, AOOf, EOOp, AOOp, EOOp, AOOp were calculated. These procedures were carried out in the R packages “ecospat” (Broennimann et al. 2020) and “red” (Cardoso 2020).

**Gap analysis** – The previously generated binarized models were used as basis for GA calculation. This enables greater parameterization of the analysis and higher fidelity in result comparison, in addition to ensuring more reliable results as the binary models follow a calculated threshold. The anthropized areas (BDiA 2020) were removed from the binarized models to avoid inserting areas where the species certainly do not occur, i.e., only suitable areas with anthropogenic absence were used in the analysis. The layers resulting from this process were overlapped with the PAs (ICMBio 2020), and PAs occurring in suitable areas were identified and extracted. The percentage of protected areas within the environmental suitability area for each species was then calculated. The next step was to identify which species are present within PAs and calculate how many records represent the presence of the species in these areas. All these procedures were performed using the software QGIS 3.12.0 (QGIS Development Team 2020).

**Cartographical procedures** – *Eremanthus erythropappus* was selected as an example to cartographically represent the results obtained here, as it is the better known and exploited *Eremanthus* species. Maps representing the results for other *Eremanthus* species are available in the Online Resource 1–30. Maps were designed using the software QGIS 3.12.0, using the data generated in the previous analyses.

### 3 Results

**SDMs and environmental suitability** – The SDM results for the present were consistent with the records, showing wider areas of suitability in relation to the current distribution of the species and in agreement with the Cerrado distribution. The Espinhaço Range was the region which more frequently appeared in the models as an area conducive to the establishment of the species, especially the Espinhaço Meridional, including for *Eremanthus cinctus* (Online Resource 3), *E. goyazensis* (Online Resource 13), *E. mattogrossensis* (Online Resource 17), *E. mollis* (Online Resource 19) and *E. uniflorus* (Online Resource 29), which currently do not have records in this geological formation. The Eastern Cordillera in Bolivia was an important present area of suitability in the models of *E. cinctus*, *E. mattogrossensis* and *E. rondoniensis*, with the exception of *E. cinctus* in the future simulation, which did not show significant suitability in that region (Online Resource 3–4, 17–18, 25–26). *E. mattogrossensis* showed a large variation in SDM results in the time periods, presenting a wider suitability in the present, and high reduction in suitability estimated for the future (Online Resource 17–18).

In relation to the results presented by the future SDM models, a great decrease in the environmental suitability area was observed for all species in all RCP scenarios when compared to the present models. The loss of suitability between models at the different RCP levels was relatively similar and with a gradual increase from the RCP 2.6 level (more optimistic scenario) to the RCP 8.5 level (more pessimistic scenario). Almost all species showed the decrease of suitability area to a very reduced region between the states of Minas Gerais, Rio de Janeiro and São Paulo, especially in areas of Serra da Mantiqueira and Serra do Mar (see electronic supplementary material). *E. cinctus* (Online Resource 4), *E. goyazensis* (Online Resource 14), *E. mollis* (Online Resource 20) and *E. uniflorus* (Online Resource 30) show a trend to disappear from the current distribution areas, with a more critical situation for the latter, which will practically lose the entire adequacy area where current records are located. The Eastern Cordillera showed a high level of suitability in the future projection of *E. rondoniensis*, while the areas of suitability in Brazil were significantly reduced (Online Resource 26). The future projection of *E. capitatus* showed a great extent of adequacy area, however, with a low adequacy index for the most part (Online Resource 2).

*Eremanthus erythropappus* presented a well-marked area of environmental suitability for the present model, showing highlighted areas in the Espinhaço Meridional, Serra da Mantiqueira, Serra do Mar, Serra da Canastra and towards Brasília (Fig. 2). Projections for the future estimate a drastic reduction in the suitability area of about 75% compared to the present, with restriction to the northeast portion of São Paulo, Serra da Mantiqueira and Serra do Mar (Fig. 3; Table 2).

**Gap Analysis: Records and PAs** – Present: With the exception of *E. uniflorus*, all other species presented less than 50% of their records within PAs (Table 2). The highest and lowest percentage of records in PAs were found in *E. uniflorus* (72%) and *E. cinctus* (8%), respectively. All species showed low percentages of PAs in areas of suitability, with values between 12% (*E. mattogrossensis*) and 27% (*E. erythropappus*).
erythropappus) and the majority presenting values below 25%. The average percentage of records in PAs was 31%, and the average percentage of suitability areas contained in PAs was 18% (Table 2).

**Future:** The results presented here reflect a stationary condition of the PAs. In view of changes in circumscription of PAs caused by climate change and public policies, the future GA values can be different. *Eremanthus cinctus, E. crotonoides, E. erythropappus, E. incanus* and *E. mollis* showed percentage values of PAs in suitability areas greater than 50% (60%, 61%, 68%, 54% and 56%, respectively). The other species showed values between 25% (*E. rondoniensis*) and 49% (*E. glomerulatus*), with an average percentage of 46%. The projected percentages of suitability area loss and PA loss in relation to suitability areas were evaluated. The lowest and highest percentages of suitability area loss were 51% for *E. rondoniensis* and 97% for *E. matto grossensis*, with an average value of 82% among all species. *Eremanthus uniflorus* and *E. rondoniensis* presented the highest and lowest percentage values of PA loss with 93% and 2%, respectively, and the average among all species was 59% (Table 2).

**EOO, AOO and IUCN red listing** – Consistent values of EOO and AOO were obtained in all situations defined for this study. The values found for AOO were sufficient to fit the species in the requirements of IUCN criterion B (Table 3). The EOOp, AOOp, EOOf, AOOf, EOOph, AOOfh, EOOlh and AOOfh results allowed us to identify a projected decline in EOO and AOO, due to the difference between present and future values. All species presented considerable EOO and AOO losses. The projections show an average percentage of total area EOO and AOO loss (EOOtl and AOOtl) of 60% and 83%, respectively, and of 71% and 89% for the area belonging to MCP records (EOOlh and AOOlh), respectively.

When it comes to EOOf and AOOf, only *E. uniflorus* fits IUCN criterion B parameters; however, the situation considerably changes when EOOh and AOOh are used. In this case, *E. cinctus, E. goyazensis, E. mollis* and *E. uniflorus* fit the geographic limitation criterion for both measurements, while *E. elaeagnus, E. polycephalus* and *E. syncephalus* are classified under the same criterion only with AOOfh values. In this situation, *E. cinctus* and *E. uniflorus* are the most...
The future scenario of an iconic tree from the Brazilian Cerrado: perspectives on *Eremanthus*…

**Fig. 3** *E. erythropappus* future (2070–RCP 8.5) suitability areas and Gap Analysis results. The grey-scale areas show the environmental suitability of Species Distribution Modelling (SDM), with intensity corresponding to the map scale. Darker areas indicate higher environmental suitability. The line surrounding the environmental suitability area represents the modelling Minimum Convex Polygon (MCP) and the dashed line corresponds to records MCP. The areas suitable for species establishment are in blue and protected areas (PAs) are in red. Brazilian states: BA, Bahia; ES, Espírito Santo; GO, Goiás; MG, Minas Gerais; MS, Mato Grosso do Sul; MT, Mato Grosso; PR, Paraná; RJ, Rio de Janeiro; RS, Rio Grande do Sul; SC, Santa Catarina; SP, São Paulo; TO, Tocantins

**Table 2** Percentage values found for records in protected areas (Records PAs), protected areas in suitability area for present and future models (Present PAs and Future PAs) and suitability area loss estimated for total area and protected areas (TAs Loss and PAs Loss) related to SDM models.

| Species          | Records PAs (%) | Present PAs (%) | Future PAs (%) | TAs loss (%) | PAs loss (%) |
|------------------|-----------------|-----------------|----------------|--------------|--------------|
| *E. capitatus*   | 21              | 14              | 28             | 89           | 79           |
| *E. cinctus*     | 8               | 15              | 60             | 96           | 86           |
| *E. crotonoides* | 26              | 20              | 61             | 82           | 48           |
| *E. elaeagnus*   | 35              | 19              | 47             | 75           | 40           |
| *E. erythropappus* | 28             | 27              | 68             | 74           | 38           |
| *E. glomerulatus*| 41              | 16              | 49             | 91           | 74           |
| *E. goyazensis*  | 37              | 17              | 42             | 92           | 81           |
| *E. incanus*     | 26              | 18              | 54             | 86           | 60           |
| *E. mattogrossensis* | 22         | 12              | 41             | 97           | 92           |
| *E. mollis*      | 36              | 17              | 56             | 92           | 77           |
| *E. polycephalus*| 29              | 12              | 38             | 83           | 51           |
| *E. reticulatus* | 25              | 22              | 37             | 53           | 21           |
| *E. rondoniensis*| 26              | 12              | 25             | 51           | 2            |
| *E. synccephalus*| 33              | 26              | 47             | 68           | 43           |
| *E. uniflorus*   | 72              | 22              | 34             | 95           | 93           |

PA, protected area; TA, total area
critical cases, with total absence of these two species within the areas of the convex hull of records in future estimates.

EOOr, EOOp, AOOp and AOOph results were not significant for classification under IUCN criterion B. Thus, the species of the *Eremanthus* classified in IUCN criterion B2b(i,ii), considering AOOr results and the projected EOO and AOO reductions, were *E. capitatus*, *E. crotonoides*, *E. erythropappus*, *E. glomerulatus* and *E. incanus* in the Vulnerable (VU) category and *E. cinctus*, *E. elaeagnus*, *E. goyazensis*, *E. mattogrossensis*, *E. mollis*, *E. polycephalus*, *E. reticulatus*, *E. rondoniensis*, *E. syncephalus* and *E. uniflorus* in the Endangered (EN) category (Table 3). Currently, IUCN presents a conservation status classification for *E. auriculatus*, *E. crotonoides*, *E. goyazensis*, *E. mattogrossensis*, *E. mollis*, *E. polycephalus*, *E. reticulatus*, *E. syncephalus* and *E. umiflorus* in the Least Concern (LC) category, for *E. auriculatus* and *E. praetemissus* in the Vulnerable (VU) category, for *E. argenteus* and *E. veadeiroensis* in the Endangered (EN) category and for *E. brevifolius* and *E. ovatifolius* in the Critically Endangered (CR) category. CNCFlora classifies *E. capitatus* and *E. crotonoides* as LC, *E. argenteus* as EN and *E. polycephalus* and *E. seidelii* (= *E. elaeagnus*) as VU (Martinelli and Moraes 2013).

### Table 3

| Species          | EOOr (km²) | AOOr (km²) | IUCN category | EOOtl (%) | AOOtl (%) | EOOhl (%) | AOOhl (%) |
|------------------|------------|------------|----------------|-----------|-----------|-----------|-----------|
| *E. capitatus*   | 885,507    | 616        | VU             | 30        | 89        | 65        | 94        |
| *E. cinctus*     | 360,580    | 48         | EN             | 94        | 92        | 100       | 100       |
| *E. crotonoides* | 519,587    | 516        | VU             | 75        | 77        | 75        | 90        |
| *E. elaeagnus*   | 125,365    | 204        | EN             | 56        | 85        | 77        | 90        |
| *E. erythropappus* | 690,176    | 584        | VU             | 50        | 81        | 62        | 85        |
| *E. glomerulatus* | 777,541    | 612        | VU             | 59        | 87        | 66        | 91        |
| *E. goyazensis*  | 357,086    | 296        | EN             | 74        | 80        | 96        | 96        |
| *E. incanus*     | 439,893    | 508        | VU             | 57        | 90        | 66        | 93        |
| *E. mattogrossensis* | 1,692,804  | 312        | EN             | 49        | 90        | 69        | 95        |
| *E. mollis*      | 202,975    | 132        | EN             | 81        | 85        | 98        | 98        |
| *E. polycephalus* | 92,945     | 140        | EN             | 48        | 88        | 51        | 92        |
| *E. reticulatus* | 104,652    | 64         | EN             | 35        | 65        | 34        | 53        |
| *E. rondoniensis* | 90,008     | 72         | EN             | 61        | 59        | 65        | 79        |
| *E. syncephalus* | 168,166    | 124        | EN             | 35        | 81        | 39        | 87        |
| *E. uniflorus*   | 32,071     | 40         | EN             | 98        | 91        | 100       | 100       |

EOO, extent of occurrence; AOO, area of occupancy; MCP, minimum convex polygon; VU, vulnerable; EN, endangered; h, convex hull (MCP); l, loss percentage; r, records; t, total area

#### 4 Discussion

It is important to highlight that anthropogenic threats continue to intensify in Cerrado, mainly due to mining, which drastically changes the natural landscape by modifying the relief, removing soil and vegetation, and the use of alien grasses for pasture and deforestation caused by agriculture expansion (Ratter et al. 1997; Pivello et al. 1999; Pena et al. 2017). These environmental problems need to be contained and some habitat recovery initiatives have been implemented over the years but restoring the natural conditions of botanical communities is difficult and further impaired by the threat of ruderal invasive species (Silveira et al. 2016). Furthermore, the Brazilian savannas are extremely important for global biodiversity and are especially crucial in the context of conservation: they harbour thousands of endemic species resulting from a long historical process and are in serious risk of disappearing in the coming decades due to the slowness of conservation actions (Mucina and Wardell-Johnson 2011; Hopper et al. 2016; Silveira et al. 2016). Despite this being widely known, the savannah areas in Brazil present few protection units and low representation of endangered species in these areas, which reinforce the idea that PAs are not effective in protecting biodiversity (Françoso et al. 2015; Neves et al. 2018).

These findings can be observed in *E. erythropappus*, which is the species subjected to greater anthropogenic
threats among those studied here due to indiscriminate wood extraction, being the subject of several conservation studies (Scolforo et al. 2002; Pádua et al. 2016) (Fig. 1e). This species is commonly found in soils with high heavy metal concentrations (Machado et al. 2013). This characteristic influences the way in which sustainable management projects are implemented (Araújo et al. 2018). Therefore, it needs to be considered when applying revegetation methods for conservation purposes. This information helps to comprehend the current scenario of the species and to develop studies such as population genetics and understand microevolutionary processes that can influence in the conservation of species like *E. erythropappus*, informing how populations should be managed. Another approach is to develop studies of functional traits, because they can show how the environment promotes variation in species morphology (Borges et al. 2018; Rocha et al. 2020a, b). However, scientific research is a component of conservation projects and a concerted effort between the government, the private sector and the society is needed for the preservation of this species, which otherwise will likely disappear from nature (Carvalho et al. 2019).

Allied to that, the future projections show a dire scenario not only for *E. erythropappus* but many species of the genus. The expected suitability areas for *Eremanthus* are very small, and some species will likely become extinct in the natural environment, such as *E. uniflorus*. Additionally, these areas present a much lower potential for suitability when considering the GA results, further aggravating the situation, as PAs might not be effective to protect species, due to the reduced percentage of records in them (Oliveira et al. 2017). This problem can be worse because these favourable suitability areas are in regions with high levels of anthropogenic activity and few preserved areas. Likely many species of *Eremanthus* will not be able to reach areas of future suitability and establish in the areas identified by GA. Given that our results consider the current situation of anthropogenic areas and conservation units in the future projections, the conservation situation of *Eremanthus* species is expected to become more critical in the coming decades. Related to that, a common issue for species likely to be subjected to future distribution restrictions is AOO volatility, i.e., differences in species distribution along time in restricted and environmentally impacted areas cause an oscillation of the future estimated AOO (Marco et al. 2018), and this will probably be the case of *Eremanthus*.

These environmental scenarios found for *Eremanthus* species present similar results to those of Carvalho et al. (2019), especially in the drastic reduction of projected future suitability areas. This requires immediate conservation actions, as these scenarios show a restriction of the distribution of the species to the regions of Serra da Mantiqueira and Serra do Mar, and their disappearance in several areas where they are currently distributed (Figs. 2, 3). We also obtained similar results to those of Bitencourt et al. (2016), with the majority of the suitability areas for *campos rupestres* in the Espinhaço Range but also in other areas such as Serra da Caanastra (state of Minas Gerais) and Chapada dos Veadeiros (state of Goiás), and the projection of great losses of suitability area (including the few PAs of the Espinhaço Range) with the *campos rupestres* almost exclusive in the Espinhaço Meridional (barely present in the northern and outside of the Espinhaço Range) and a high potential of species extinction in *campos rupestres* due to habitat loss. This coincides with the fact that a small number of endemic species are protected by PAs and many of these areas may become less effective due to climate change, and therefore, conservation actions need to consider the representativeness and ecology of the species (Bitencourt et al. 2016). These inferences need to be considered for *Eremanthus*, as the presence of its species in PAs is also low and can be affected by climate change in the coming decades.

Some studies carried out recently have brought evidence that the edaphic component can be a differential in the face of climate change. Species distributed in areas considered challenging, such as the Cerrado and *campos rupestres*, are quite well adapted to the soil conditions, being a limiting factor for their dispersion and consequently, making them more susceptible to environmental threats (Corlett and Tomlinson 2020; Rapini et al. 2021). Thus, adaptive radiation found in groups composed of edaphic specialist species was likely promoted by heterogeneity of soil composition and not necessarily by climatic fluctuations that occurred over geological periods (Rapini et al. 2021). Thus, it is possible that this edaphic factor increases the vulnerability of the genus *Eremanthus*, since the group is composed by several species present in specific edaphic conditions and may have their dispersal capacity compromised as a result of their adaptation to the soil and inability to establish in other areas.

Considering these aspects mentioned above and our data, the use of SDM as a tool for classifying *Eremanthus* species in IUCN criterion B2b(i,ii) was effective, especially regarding the assessment of species spatial distribution and the future behaviour of EOO and AOO in relation to extinction risks. SDM showed a projected decline for EOO and AOO, both being essential components for IUCN classification (IUCN Standards and Petitions Committee 2019). Furthermore, the results showed that AOOr values were indispensable to classify species of *Eremanthus* in threatened species lists, as none of the EOOr results met IUCN requirements (Kaky and Gilbert 2019). It is also important to notice that, when comparing EOOp, AOOph, EOOfh and AOOfh with EOOp, AOOp, EOOf and AOOf it is evident that the manner in which the MCP of the SDM models is delimited greatly
influences results, when considering the criterion B parameters (Fivaz and Gonseth 2014).

This understanding about Eremanthus was possible with the help of the SDM, which estimates areas of suitability using quantitative values and serves as an objective resource in IUCN assessments that aim to understand the relationship of the species with the environment (Sangermanno and Eastman 2012). Looking at these results, it is important to note that the integrative application of SDM, GA and IUCN red listing allows the visualization of the current distribution of the species and their future behaviour in the face of environmental conditions, in addition to contributing to conservation management by identifying the percentage of PAs within EOO and AOO (Marcer et al. 2013). Furthermore, these results serve as a basis for planning conservation strategies with greater preparation and effectiveness, especially when it comes to developing countries where research is scarce (Fivaz and Gonseth 2014). However, to achieve reliable results, EOO and AOO measurements using SDM models need to be performed with care (Kaky and Gilbert 2019).

Taking this into account, some issues should be noted even though our methodological approaches were positively integrated with solid results. SDM can generate a wide range of models with different environmental suitability probabilities, and therefore, it must be carefully prepared and evaluated, especially regarding the choice of environmental layers, which should consider the actual condition of the species (Fivaz and Gonseth 2014; IUCN Standards and Petitions Committee 2019). Depending on the level of the RCP used for the future projections, the generated models can result in conflicting environmental suitability conditions that can directly influence other analyses (Kaky and Gilbert 2019; Moat et al. 2019). Furthermore, the use of different algorithms may also influence research results and interpretations and should therefore be chosen appropriately (Elith and Leathwick 2009). The two-stage cleaning process applied to the database is essential for result credibility and accuracy, especially in species extinction risk assessment (Panter et al. 2020). Thus, the records should be properly filtered to eliminate possible errors, as the geographic location of the species directly influences MCP, EOO and AOO values and consequently the fitting of the species in IUCN red list categories (Fivaz and Gonseth 2014). Additionally, the effects of species sampling on SDM performance and accuracy and the use of statistical evaluation criteria for the models should be considered (Stockwell and Peterson 2002; Allouche et al. 2006; Wisz et al. 2008).

In addition to the aforementioned methodological factors, the absence of data in the SDM that portray the species biotic factors compromises the real prospects of how species can overcome environmental threats, especially in future estimates, as the effects and constraints of these biotic relationships can be ignored (Elith and Leathwick 2009; Sinclair et al. 2010). Populations and species are subject to the consequences of natural selection, contributing to the reduction of the risk of extinction of species as they can adapt to environmental changes even in scenarios of accelerated modification (Etterson and Shaw 2013; Bemmels and Anderson 2019; Fox et al. 2019). In which case, the SDM models may overestimate environmental losses and species extinctions by not considering potential genetic adaptations in response to environmental changes, and incorporating genomic data into the analysis may increase the reliability of the results (Razgour et al. 2019). Inclusion of approaches involving evolutionary processes and local adaptations of species in the SDM demonstrate that the risks of environmental vulnerability presented in the models are reduced, which contribute significantly to a better species dynamic interpretation (Bush et al. 2016; Peterson et al. 2019; Chen et al. 2020). These factors, along with other variables such as migration, genetic drift and population dynamics, contribute to the change in species distributions of future predictions, since these factors are dynamic, unpredictable and can be incorporated into the SDM, generating different interpretations (Bush et al. 2016; Razgour et al. 2019).

Despite all these observations, the results presented here are positive from the perspective of their applicability as a scientific contribution and, along with previous research, reinforce the pertinence of SDM for application of IUCN Red List Criteria (Marcer et al. 2013; Fivaz and Gonseth 2014; Syfert et al. 2014; Marco et al. 2018; Kaky and Gilbert 2019; Moat et al. 2019). Future studies that investigate the populational dynamics of Eremanthus may be the path to complete the necessary requirements for including species of the genus in IUCN Red List Criteria. These analyses could also be performed using soil data in order to better understand the importance of edaphic adaptation in Eremanthus species.

In view of the results obtained here, the present and future suitability areas found in the SDM allowed the identification of regions for species establishment; however, a significant part of these areas has some degree of anthropogenic interference. Therefore, a small percentage of the suitability areas is available for species occupation, with an even smaller fraction of these areas within PAs, which explains the current low proportion of species records in conservation units. Moreover, the future prospect is dire in relation to species sustainability in nature. Thus, classifying threatened species using the IUCN Red List criteria, even if partially, is essential for the elaboration of strategies for preparation and application of conservation-oriented policies and prevention of environmental damage. It is also important to mention that the Espinhaço Range, core area of the Eremanthus distribution, harbours several threatened plant groups in an important physiognomy that needs to be better scientifically understood for preservation purposes.
Thus, the results obtained through the integration of different methodologies provide the basic framework for their application in conservation models.

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**Declarations**

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