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O IMPACTO DA IMPLEMENTAÇÃO DO CÓDIGO FLORESTAL NA MITIGAÇÃO DOS EFEITOS DAS MUDANÇAS CLIMÁTICAS NA FLORA DO CERRADO

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EMILLY LAYNE MARTINS DO NASCIMENTO

O IMPACTO DA IMPLEMENTAÇÃO DO CÓDIGO FLORESTAL BRASILEIRO NA MITIGAÇÃO DOS EFEITOS DAS MUDANÇAS CLIMÁTICAS NA FLORA DO CERRADO

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Orientadora: Prof.ª Dr.ª Geiziane Tessarolo

Co-Orientador: Prof. Dr. Santiago José Elías Velazco

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SUMÁRIO

RESUMO

O bioma Cerrado abriga um grande número de espécies endêmicas, no entanto apesar de sua importância há uma grande perda de habitat, isso devido ecossistemas serem afetados por ações antrópicas, tais como a substituição de áreas naturais e as mudanças climáticas, que também são uma preocupação pois atingem os ecossistemas e ameaçam à biodiversidade provocando alterações na distribuição das espécies com o potencial de levar à extinção. A combinação das mudanças climáticas com redução de áreas naturais ocasiona uma diminuição da diversidade biológica e extinções locais de plantas, sendo o Cerrado um dos biomas mais afetados com perda de área natural. Nesse trabalho avaliamos como a distribuição das espécies da flora endêmicas e ameaçadas do Cerrado será afetada pelas mudanças climáticas e como as mudanças no uso do solo em diferentes cenários de implementação do código florestal contribuirá para mitigar as consequências das alterações climáticas, evitando no futuro a perda da distribuição das espécies. Desenvolvemos mapas de riqueza de espécies para diferentes cenários de emissão, sendo um cenário otimista (SSP126), um intermediário (SSP245) e um pessimista (SSP585) projetados para o ano de 2050 para 242 espécies endêmicas e ameaçadas do Cerrado. Além disso, analisamos a mudança na distribuição das espécies incorporando dois cenários de uso do solo, relativos à implementação do código florestal, cenários baseline - controle de desmatamento e FC - implementação total do código florestal. O cenário baseline considera que o controle do desmatamento ilegal é imperfeito ou parcial e o cenário FC considera a plena implementação do código florestal, com restauração de áreas desmatadas e permitindo apenas o desmatamento legal. Os diferentes cenários de uso de solo irão levar a uma menor perda de distribuição, a implementação do código, tanto parcial quanto total, melhora a proteção e conservação das espécies. A maioria das espécies (239) terão sua distribuição reduzida mesmo nos melhores cenários (cenário de emissão otimista SSP126 e com implementação total do código florestal). Não haverá nenhuma mudança na distribuição de três espécies apenas, enquanto oito espécies serão extintas, sendo que 76 espécies perderão mais de 75% da área adequada, no cenário de FC com SSP585. No entanto, quando apenas o cenário climático é levado em conta, 53 espécies perderão mais de 75% da área adequada no cenário de emissão SSP585. As regiões sul e sudeste do Cerrado brasileiro serão as áreas com maior adequabilidade climática futura para espécies. Consequentemente, a conservação das espécies, que são endêmicas e já classificadas como ameaçadas no Cerrado, será ainda mais afetada.

Palavras-chave: Savana, Mudanças climáticas, Modelos de distribuição das espécies, Mudança do uso da terra, Código Florestal Brasileiro.

ABSTRACT

The Cerrado biome is home to a large number of endemic species. However, despite its importance, Cerrado suffers a significant habitat loss due to ecosystems being affected by anthropic actions, such as replacing natural areas and climate change. The combination of climate change and the reduction of natural areas causes a decrease in biological diversity and local extinctions of plants. The Cerrado is one of the biomes most affected by the loss of natural areas. Here we evaluate how the distribution of endemic and threatened flora species of the Cerrado will be affected by climate change and how changes in land use in different scenarios of forest code implementation will contribute to mitigating the consequences of climate change. We developed species richness maps for three emission scenarios, an optimistic (SSP126), an intermediate (SSP245), and a pessimistic (SSP585) scenario projected to the year 2050 for 242 endemic and threatened Cerrado species. In addition, we analyzed the change in species distribution incorporating the different land use scenarios relative to the implementation of the forest code, baseline scenarios - deforestation control, and FC - full forest code implementation. The baseline scenario considers that control of illegal deforestation is imperfect or partial, and the FC scenario considers full forest code implementation, with restoration of deforested areas and allowing only legal deforestation. The different land use scenarios will lead to less distribution loss; partial and full forest code implementation could improve species protection and conservation. Most species (239) will have their distribution reduced in the best scenarios (optimistic emission scenario and with full implementation of the forest code). There will be no change in only three species, while eight species will become extinct, with 76 species losing more than 75% of their suitable area, in the FC scenario with SSP585. However, if only the climatic scenario is taken into account, there will be a reduction in distribution, and 53 species could lose >75% of the suitable area in the SSP585 emission scenario. The southern and southeastern regions of the Brazilian Cerrado will be the areas with future climatic suitability for most species. Consequently, the conservation of species, which are endemic and already classified as threatened in the Cerrado, will be further affected.

Keywords: Savanna, Climate change, Species distribution models, Land use change, Brazilian forest code

INTRODUÇÃO GERAL

Cientistas preveem que os impactos à biodiversidade tendem a aumentar nas próximas décadas, devido principalmente às mudanças climáticas e no uso do solo (PECL *et al.*, 2017; NEWBOLD, 2018). As mudanças climáticas estão cada vez mais acentuadas e em um futuro próximo seus impactos serão possivelmente mais acentuados (NEWBOLD, 2018), e podem de forma isolada levar a uma drástica redução na área de distribuição das espécies (WARREN *et al.,* 2018; ROMÁN-PALACIOS; WIENS, 2020). Além disso, as mudanças no clima afetam as espécies de várias formas, alteram as distribuições, o tempo dos eventos de seus ciclos de vida, tais como: migração e reprodução que acarreta na extinção de populações locais (CAHILL *et al*., 2013; PARMESAN, 2006). É esperado que os impactos das mudançcas climáticas se intensifiquem, uma vez que as projeções climáticas indicam um aumento na temperatura global dependendo do cenário de emissão de gases de efeito estufa (IPCC, 2021).

Em contrapartida, a mudança no uso do solo com perda e fragmentação de habitas é considerada o principal impacto humano na ameaça à biodiversidade (NEWBOLD *et al*., 2019). As modificações no uso da terra no Cerrado quando associadas ao aumento da frequência de incêndios provocam profundas mudanças na estrutura da vegetação e no funcionamento de seus ecossistemas (BUSTAMANTE *et al*., 2012). A combinação das alterações climáticas e uso do solo pode piorar ainda mais o impacto sobre a biodiversidade. Por isso a avaliação conjunta desses processos se faz necessária para a proposição de ações efetivas de conservação (NEWBOLD, 2018).

O Cerrado, hotspots de biodiversidade, com alta taxa de endemismo para espécies de plantas ameaçadas (MYERS *et al.,* 2000) está localizado na região central do Brasil, uma região de alta instabilidade climática futura e alta degradação da vegetação natural atual (WATSON *et al.,* 2013). Atualmente esse bioma possui somente ~20% de sua vegetação nativa sem degradação (STRASSBURG *et al*., 2017), enquanto vem sofrendo um aumento da pressão para expansão agrícola, o que combinado com uma baixa proteção por lei de sua vegetação, pode levar a uma perda de >30% de sua vegetação nativa remanescente (FRANÇOSO *et al*., 2015, SOARES-FILHO *et al.,* 2016; STRASSBURG *et al*., 2017).

Entre as principais ferramentas para mitigar os efeitos dessas ameaças estão a criação de áreas protegidas e a implementação de políticas, regulamentações e leis (PIMM; JENKINS; LI, 2018; BROCK *et al*., 2021). No Brasil, a lei de Proteção da Vegetação Nativa (mais conhecida como Código Florestal Brasileiro; lei federal n.12,651/12) é o principal mecanismo de regulamentação no uso e proteção de vegetação nativa em propriedades privadas. Embora essa lei se diriga somente às áreas privadas, ela é extremamente importante na conservação da biodiversidade, uma vez que ~53% da vegetação nativa brasileira ocorre em propriedades rurais particulares (SPAROVECK *et al.*, 2015). Portanto, a implementação do novo código florestal pode impactar mudanças no uso da terra e consequentemente na conservação da biodiversidade brasileira. Embora tenha sido aprovada em 2012 a completa implementação do código florestal ainda não aconteceu e segue gerando discussões devido a conflitos de interesse de diversos grupos (BRANCALION *et al.*, 2016), o que tem gerado a proposição de alterações de diversos artigos da lei e, consequentemente, a instabilidade sobre a implementação da mesma (SOARES-FILHO *et al.*, 2014; RODRIGUES; MATAVELLI, 2020).

Considerando a importância e vulnerabilidade das espécies endêmicas e ameaçadas da flora do bioma Cerrado frente às mudanças climática e no uso da terra, e os possíveis impactos da implementação do código florestal na mitigação dessas ameaças, nesse trabalho nós avaliamos o impacto das mudanças climáticas e do uso do solo em diferentes cenários de implementação do código florestal na distribuição de espécies da flora endêmica e ameaçada do Cerrado.

THE EFFECT OF THE BRAZILIAN FOREST CODE ON THE MITIGATION OF CLIMATE CHANGE EFFECTS ON THE CERRADO FLORA

Emilly Layne Martins do Nascimento, Santiago José Elías Velazco, Fernando Manuel Ramos &
Geiziane Tessarolo

Introduction

Threats to biodiversity can lead to high extinction rates. The impacts predictions of climate change and land use must be indicative because their effects can be complex and synergic. Therefore, their interactions are determinants of the biodiversity crisis (HE *et al.*, 2019). The human influence on climate has been evident and unprecedented in recent years. The increase in global temperature predicted for the coming decades is higher than the average recorded during the entire Holocene (IPCC, 2021). Climate change affects ecosystems and threatens biodiversity as it can cause distribution changes and potentially drive many species to extinction (WANG *et al.*, 2012; CAHILL *et al.*, 2013; SAGE, 2020). In response to climate changes, plant species are susceptible to phenological changes that alter their life cycles (PARMESAN, 2006). Consequently, species interactions and community composition are affected (DEVICTOR *et al.*, 2012). Additionally, climate change affects human well-being by causing changes in natural resources (e.g., food) and disease transmission (PECL *et al.*, 2017).

Habitat loss and land use changes are the leading causes of worldwide flora extinction (LE ROUX, *et al.*, 2019). Habitat loss has a consequence on the local extinction risk of vascular plant species (STAUDE; NAVARRO; PEREIRA, 2019). Global change scenarios predict that habitat loss and climate change will be intensified by the end of the century and would cause the extinction of thousands of species (OLIVER and MORECROFT, 2014). However, future extinctions could be reduced by incorporating habitat preservation to decrease predicted land use changes in hotspots or soften the land use impact on biodiversity (JANTZ *et al.*, 2015)

The Brazilian Cerrado is one of the biodiversity hotspots (MYERS *et al.*, 2000; STRASSBURG *et al.*, 2017). Cerrado is the second largest biome in Brazil (SANO; ALMEIDA; RIBEIRO, 2008; DAMASCO *et al.*, 2018) and according to the Brazilian Flora (2020) is home to >13.000 plant species, 44% of which are endemic (MYERS *et al.*, 2000; KLINK; MACHADO, 2005). Such diversity makes this biome the richest savanna in the world (KLINK; MACHADO, 2005; DAMASCO *et al.*, 2018). Despite its importance, the biome struggles with a significant habitat loss of 46% of its native vegetation, and by 2050, up to 34% of the remaining natural areas may disappear, leading to the largest extinction of plants in history (STRASSBURG *et al.*, 2017). Habitat loss and fragmentation are the main threats to all existing biota in the Cerrado (COSTA *et al.*, 2005). The Cerrado is being destroyed at a rate far more than the scientific community's ability to promote the knowledge necessary for its protection and conservation (DE SOUZA AGUIAR *et al.*, 2004). If the Brazilian Cerrado's deforestation rate remains as today, it may record the greatest global loss of plant species since the rate is higher than other Brazilian biomes (STRASSBURG *et al.*, 2017).

Thus, the threat of climate change combined with natural land loss can severely impact biological diversity (PECL *et al.*, 2017) and lead to local plant extinctions (LADWING, *et al.*, 2018). Indeed, a recent study showed that future climate change combined with land use could affect the flora of the Cerrado, even if in optimistic scenarios (VELAZCO *et al.*, 2019). Such predictions can be exacerbated because only 2.2% of the biome is protected by law, and 20% of endemic species are represented within protected areas (MACHADO *et al.*, 2004; KLINK; MACHADO, 2005). Thus, the conservation of species of the Cerrado flora is seriously threatened.

The Brazilian Forest Code, reformulated in 2012, aims to contribute to biodiversity conservation, climate change mitigation, and sustainable development through public policies, regulations, and laws (SOTERRONI *et al.*, 2018). Thus, implementing the forest code would be an essential public policy in mitigating the effects of land use and climate change on Brazilian biodiversity. For example, forest code implementation would reduce the loss of natural habitats for mammals, amphibians, and bird species associated with future land uses in different biomes (BROCK *et al.* 2021). Habitat loss reduction would be promoted by the code's restoration articles, which allow species to gain previously unavailable habitats. However, implementing the forest code still encounters barriers and does not occur comprehensively, decreasing the effectiveness of its biodiversity conservation goal (SOARES-FILHO *et al.*, 2014). Indeed, various project laws have been proposed to alter the forest code. However, such modifications should be carefully analyzed as any reduction scenario in the implementation of the forest code could reduce a large portion of Brazilian native vegetation, with the Cerrado being one of the biomes most affected by the loss of natural area through the decreased implementation of the forest code (BROCK *et al.*, 2021).

Considering the threat to the Cerrado flora and that the forest code is one of the most important public policies for native vegetation protection, it is essential to evaluate whether the implementation of the forest code, partially or entirely, can help to mitigate the impacts that land use and climate change may have on the Cerrado flora. We aimed to evaluate climate change's impact on the distribution of Cerrado's endangered and endemic flora species and assess if implementing the Brazilian Forest Code can contribute to mitigating its consequences.

Methods

Study area, species assessed, and occurrence data

The study area is the Brazilian Cerrado biome as delimited by *Instituto Brasileiro de Geografia e Biodiversidade* (IBGE, 2019). First, we obtained the National List of Endangered Species - Flora by Conabio Resolution 08/2021 (BRASIL, 2021). Species were categorized as endemic to the Cerrado, according to information provided by the National Center for the Conservation of Flora (CNCFlora). We selected 542 endemic and endangered species classified as trees, shrubs, subshrubs, herbs, palms, and vines. Next, species occurrence data were gathered from the Global Biodiversity Information Facility (GBIF), Botanical Information and Ecological Network (BIEN), Integrated Digitized Biocollections (iDigBio), SpeciesLink network (SPECIESLINK), Brazilian Biodiversity Information System (SiBBr), *Portal da Biodiversidade* (ICMBio), and tree flora of the Neotropical Region (NEOTROPTREE). The occurrence data resulted from work with BDC (Biodiversity Data Cleaning) package with Brazil's terrestrial plants (RIBEIRO *et al.* 2022).

The occurrence datasets were merged, and information was checked and cleaned regarding taxonomic, spatial, and temporal issues. Taxonomic cleaning consisted of syntactic correction and harmonization of specie. For specie names harmonization were used official Brazilian from the Brazilian flora as the taxonomic authority. Spatial cleaning consists of removing erroneous, suspicious, and duplicate occurrences. In addition, country data and province centroids within 2km, capitals centroids within 2km, duplicated records, equal coordinates, remove in GBIF headsquare, herbaria within 2km, outliers, coordinates zero and urban areas were removed. Finally, temporal cleaning fixed inconsistent collection dates (see RIBEIRO *et al.* 2022). Next, we filtered only the data for endemic and threatened Cerrado species.

We found occurrence data for 528 endemic and endangered species. However, many species considered endemic by CNCFlora, had occurrences in other biomes (MARACAHIPES-SANTOS et al., 2017; ARAÚJO et al., 2021; MORANDI et al., 2020), this inconsistence occurs because some species assessments are old and do not consider recent records. Thus, we evaluated species records and assessed endemism by creating a 50 km buffer around the Cerrado border (See Supporting Information Figure S1). We only considered species as endemic if at least 70% or 90% of occurrences were within the buffer for species with less than or more than ten occurrences, respectively. The species not meeting such conditions were excluded. Next, we sampled a single occurrence per grid cell (~10 km^2) for each species with package ENMTML, function “thin_occ” with the default NULL argument (ANDRADE; VELAZCO; DE MARCO JUNIOR, 2020). Then, we selected only species with at least six unique occurrences, since this quantity does not impair the generation of the species models with few points (BREINER et al., 2018). Finally, we retrieved 3,794 occurrence data for 242 species (see Supporting Information, Table S1 for the final species list).

Data on climate and soil

We used bioclimatic and edaphic variables to build niche models (ENMs), resulting in 49 variables (see Supporting Information, Table S2). We used the WordClim v2.1 (https://www.worldclim.org/) database as the source of 19 bioclimatic variables for current (1970-2000) and future conditions (2050) in a 5 arc-minute original spatial resolution. We used three emission scenarios (Shared Socio-Economic Pathways - SSPs): optimistic (126), intermediate (245), and critical (585), for eight Atmosphere-Ocean General Circulation Models (AOGCMs): BCC-CSM2-MR, CNRM-CM6-1, CNRM-ESM2-1, CanESM5, GFDL-ESM4, IPSL-CM6A-LR, MIROC-ES2L, MIROC6, MRI-ESM2-0. Edaphic physical properties (five variables at six different depths each) were sourced by SoilGrids (https://soilgrids.org/) with ~10 km original resolution. We used climatic and edaphic variables because such a combination generally improves performance of plant species distribution model and makes future model projection more reliable (BEAUREGARD; BLOIS, *et al.*, 2014; VELAZCO *et al.*, 2017; HULSHOF; SPASOJEVIC *et al.,* 2020). We only considered physical edaphic variables because they are more stable in time than chemical variables, which are more appropriate for future projections. Moreover, we used variables available for all depths because the species evaluated has a wide life spectrum (herbaceous to trees), generally having well-developed subterranean structures, such as a root system exploring great depths (SOUZA; MORAES, RIBEIRO, 2005; FURQUIM et al., 2018). Climatic and edaphic variables were standardized with 5 arc-min resolution (~ 10 km^2) through the resample function of the terra package (HIJMANS *et al.,* 2022).

We performed a principal component analysis (PCA) with the current climate and edaphic variables based on a correlation matrix to overcome the collinearity problem and reduce the number of predictor variables (DE MARCO JUNIOR; NÓBREGA, 2018). We used the eigenvectors from the PCA to calculate the scores of each derived principal component (PC). We used the nine PCs that explained >95% of the original variance as predictor variables in the distribution models. The eigenvectors from the selected PCA were used to predict scores (variables) for future scenarios. PCA was performed with “ENMTML” package (Supporting Information, Table S3; ANDRADE; VELAZCO; DE MARCO JUNIOR, 2020).

Land use data

We used land use data from the MapBiomas (https://mapbiomas.org/) collection seven for the present period and from the GLOBIOM-Brazil project for the future period (2050), both with 30 arc-second resolution. The present data source was chosen due to the correspondence between the MapBiomas classes and the GLOBIOM-Brazil downscaling classes (SOTERRONI, et al., 2018; SOTERRONI, *et al.*, 2019). GLOBIOM-Brazil is a model that simulates land use and its changes among the main sectors of the economy, which are agriculture, forestry, and bioenergy, under several historical scenarios of agricultural land demand, deforestation, and forest restoration policies for Brazil. This data is more refined for Brazilian lands than other global land use data, as it considers the regional factors influencing land use allocation. The GLOBIOM-Brazil model simulates different scenarios of forest code implementation and its impact on future land use (CAMARA *et al.*, 2015; SOTERRONI, *et al.*, 2018). Here we use two scenarios that consider the optimistic emission scenario (SSP126): Baseline – deforestation control; FC – full implementation of the forest code.

The Baseline scenario considers that control of illegal deforestation is imperfect (or partial) in the Amazon and Cerrado biomes. Furthermore, in the Amazon biome, the conversion of forests into areas for soybean cultivation is not allowed after 2005, respecting the Soybean Moratorium. In the Atlantic Forest, legal and illegal deforestation have been banned after 2011, respecting the Atlantic Forest Law (Law 11.428/2006). The FC scenario considers the full implementation of the forest code, allowing only legal deforestation and with 12Mha restoration. Like the Baseline scenario, the FC scenario also respects the Soybean Moratorium in the Amazon and the Atlantic Forest Law. The data will be used to assess how implementing the forest code can prevent the loss of suitable areas for the species predicted by distribution models.

Species distribution modeling

We modeled the distributions of 242 species using R software v.4.1.2 (R CORE TEAM, 2021) and the package “flexsdm” (VELAZCO, *et al.*, 2022). Before modeling, we delineated a calibration area for each species by a buffer of 100 km around the minimum convex polygon encompassing all the records of each species. Because we only accounted with presences data, we created pseudo-absences. Pseudo-absences were created with environmental constraints by randomly sampling in regions with lower suitability values predicted by a Bioclim model (ENGLER; GUISAN; RECHSTEINER, 2004). We sampled pseudo-absence points as the twice number of presences. This pseudo-absence selection strategy has been used successfully for species with few occurrences (LIU; NEWELL; WHITE, 2018).

We used two techniques to generate distribution modeling depending on the number of records. For species with >20 occurrences (62 species), we use the conventional method of species distribution models (SDMs) with a tuning procedure that improves the models' performance (RADOSAVLJEVIC; ANDERSON, 2014; FOURCADE, 2021). For species with occurrences between 6 to 19 (180 species), we used the Ensemble of Small Models (ESMs) modeling approach (BREINER *et al.*, 2015). ESMs are a valuable strategy for modeling the distribution of rare or poorly sampled species, as it allows for building multiple models with pair of predictors (BREINER *et al.*, 2018). ESMs create bivariate models, thus solving the problem of few occurrences and significant environmental variables causing model overfitting. ESMs perform powerfully with low occurrence samples and outperform traditional SDMs with ensemble projections, especially for rare species (BREINER *et al.*, 2015). For ESMs we used randomized data partitioning based on repeated k-folds cross-validation with five folds and five replicates. Structured partitioning methods are important for model transferability and projecting over different time periods (DE OLIVEIRA *et al.*, 2014; SANTINI *et al.*, 2021).

We used five algorithms for fitting SDMs: Generalized Linear Models (GLM), Generalized Boosted Regression (GBM), Maximum Entropy (MaxEnt), Generalized Additive Models (GAM), and Neural Networks (NET). For the conventional models, we validated the models with geographic band partitioning and only for the GBM, MAXENT and NET algorithms we fit and validate models with exploration of hyper-parameters ("tuning"). To fit Maxent algorithms, we created background points with a random allocation of 10,000 points (PHILLIPS; ANDERSON; SCHAPIRE, 2006; LIU; NEWELL; WHITE, 2018). The threshold used to obtain threshold-dependent performance metrics was the one that maximizes the sum of sensitivity and specificity because it is a method that excels when only presences are available (LIU; FOSCO; NEWELL, 2013).

The SDMs consider several aspects for prediction, among them the relationship between the species' niche and the actual distribution, and one of the associated factors is the dispersal capacity that determines the areas suitable for species. The model predictions and the actual distribution may differ, we consider the species as non-dispersers to avoid future overprediction of areas and the presence of species in places where they are not present due to dispersal limitations. To not consider dispersal we use the calibration area of each species as a cut off point for future prediction. A non-dispersal scenario is regarded as the most conservative for species protection and was chosen due to the lack of dispersal-specific data for the vast number of species (BATEMAN *et al.*, 2013).

Final models for each species for current and future conditions (i.e., for each SSP and AOGCM) consisted of a weighted average suitability (ARAÚJO; NEW, 2007; DINIZ FILHO *et al.*, 2009). We use the Sorensen metric to weight the models because the values of this metric remain similar regardless of species prevalence, and in the idealized situation where species prevalence = sample prevalence, the Sorensen similarity index is a more appropriate metric (LEROY *et al.*, 2018). Then, we averaged AOGMs prediction for future models for each SSP scenario. We calculated the threshold for ensembles and generated the ensembles for each SSP with values above the threshold that maximizes the sum of sensitivity and specificity, then transformed them into binary. We downscaled models from 10 km resolution to 30 arc-second to turn them consistent with resolution of land use data. We used "bilinear" downscaling method.

Data analysis

Impact of climate change on species

For the species distribution analysis, focusing on the relative distributional loss, we used the binary maps of presence and absence cut by the calibration area mask of each species. We developed a projected species richness map to assess occurrence relative to the present with the three SSPs. We calculated the number of cells predicted as present in current and future scenarios. We then evaluated the percentage of loss or gain of species distribution.

Impact of forest code implementation scenarios on species distribution

We calculated the association of climate with land use from Mapbiomas and under the GLOBIOM-Brazil scenarios incorporating different forest code implementation scenarios to estimate the impacts of climate and land use change on species distribution. Considering the land use classes of native vegetation and including PAs (Protection Areas), the present land use base scenario was based on the natural vegetation categories of Mapbiomas (Forest, Forest Formation, Savanna Formation, Mangrove, Wooded Sandbank Vegetation, Non Forest Natural Formation, Wetland, Grassland, Salt Flat, Rocky Outcrop, Herbaceous Sandbank Vegetation, Other non Forest Formations). In this way, models were overlaid with land use data and only presence sites with native vegetation area >30% were considered suitable for species occurrence. The same procedure was used for the future forest code implementation scenarios, considering only the Globiom natural cover. Subsequently, we projected a richness map to evaluate the relative occurrence of the species, so we accounted for the number of occurrences and the percentage of distribution loss or gain in the future. In this way, the impact of both processes (climate change and land use change), on species distribution was included, and we assessed the impact of different forest code implementation scenarios on distribution.

Results

Overall, models performed well, with an average Sorensen of 0.75 and standard deviation of 0.15 (see Supporting Information, Figure S2 for the histograms of different performance metrics). Independent of land use, most species lose part of their distribution in all climate change scenarios. Changes in land use intensify the reduction in species distribution, but the full implementation of the forest code (FC scenario) can mitigate climate change impacts, reducing species occurrence loss compared to the baseline scenario. From the 242 species assessed, 239 species had some alteration in their distribution. Considering only climate change, in the optimistic scenario (SSP126), species would lose an average of 33% (±28% SD), and reductions in distribution in 2050 tend to increase to 37% (±30%) and 41% (±33%) in the intermediate (SSP245) and pessimistic (SSP585) scenarios, respectively (Figure 1).

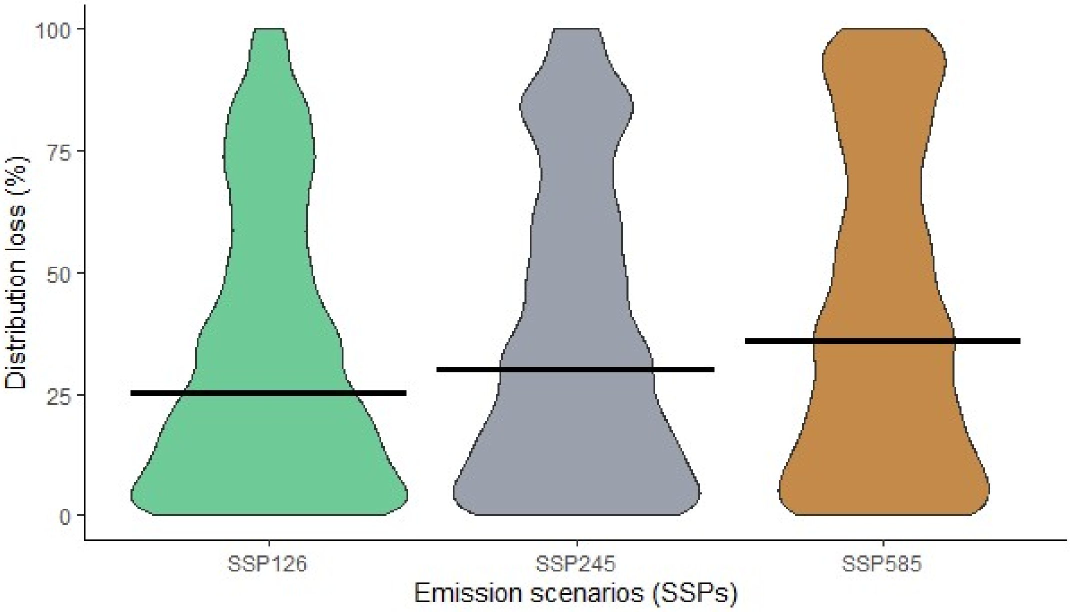

Figure 1: Percentage of species distribution loss under different emission scenarios. Black horizontal lines depict average loss.

By 2050, most species will be concentrated in the southern, southeastern, and central regions of Cerrado for all the climate change scenarios (Figure 2). Consequently, the regions with the highest richness will be those with the greatest net reductions. SSP585 estimated a larger loss distribution than SSP245 (Figure 3).

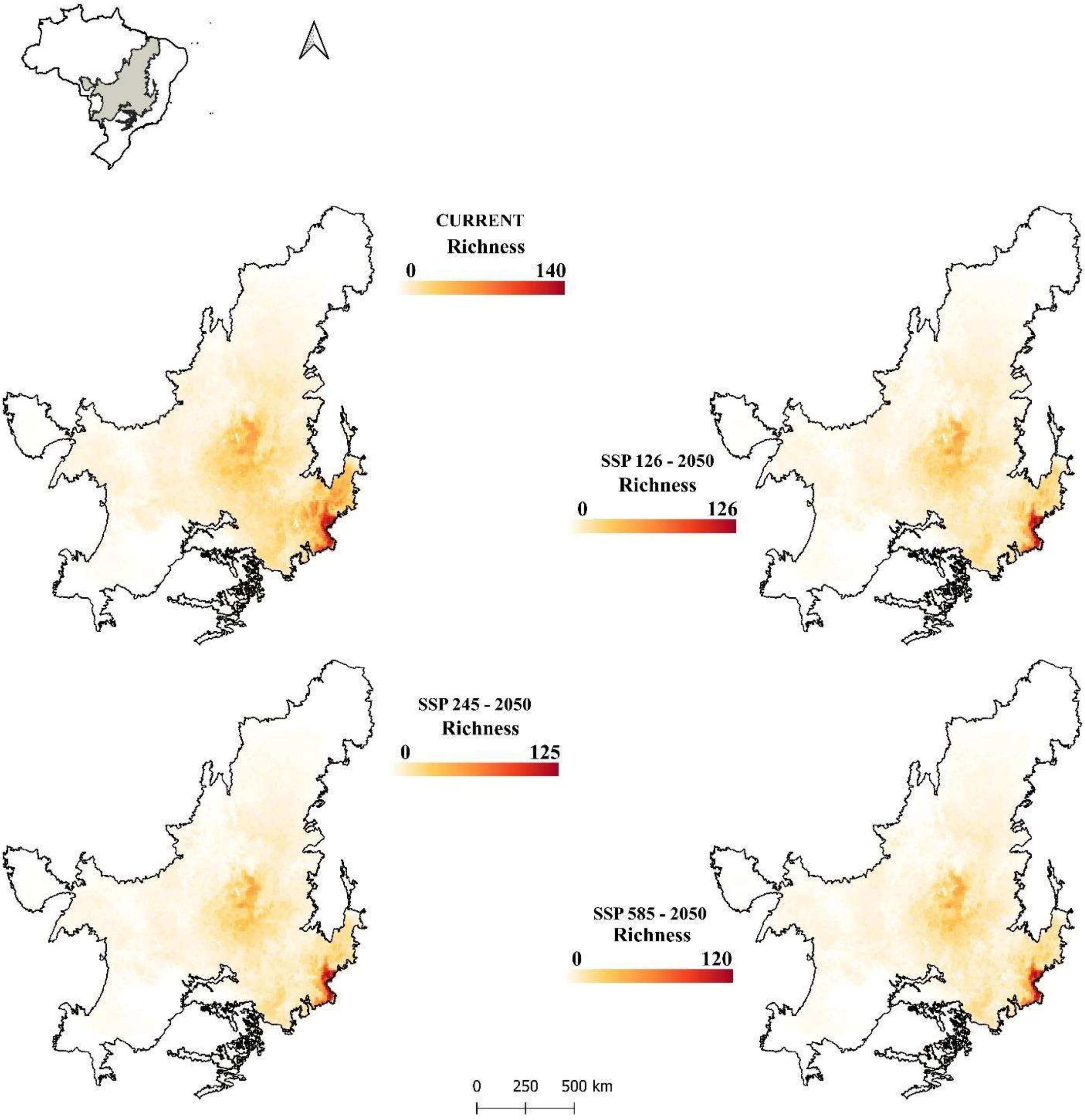

Figure 2: Richness of Cerrado endemic and endangered species for current and future emission scenarios (2050). The maximum number of species in a cell is shown for each scenario.

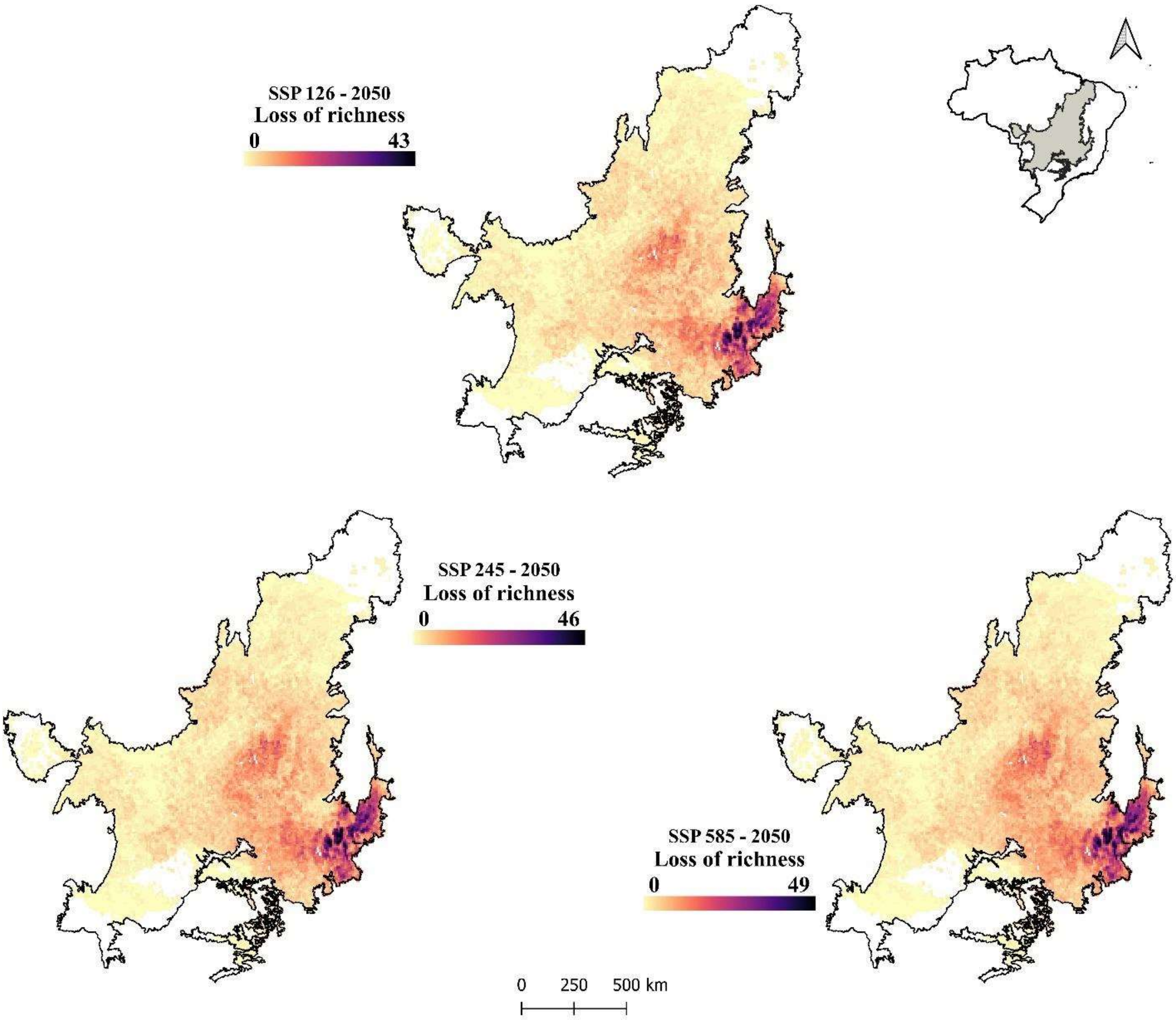

Figure 3: Loss of richness of Cerrado endemic and endangered species for current and future different emission scenarios (2050).

Considering the scenario with land use, almost all species will have their distribution reduced to some extent, even under the most optimistic scenarios. Only three species in the scenarios with land use change will not lose suitable cells, and no species in the future scenarios will gain suitable area. In the SSP585 baseline scenario, up to eight species are potentially extinct by 2050, and three in the SSP126 scenario (Table 1). In the optimistic baseline scenario (SSP126), species will lose an average of 59% (±21%) of their distribution by 2050. Distribution losses tend to increase to 61% (±22%) and 64% (±23%) in the intermediate (SSP245) and pessimistic (SSP585) scenarios, respectively (Figure 4).

Table 1. Number of species for different categories of distribution loss for future climate change scenarios only (Optimistic, Intermediate, Pessimistic) and associated with land use of forest code scenario (Baseline Optimistic, Baseline Intermediate, Baseline Pessimistic, FC Optimistic, FC Intermediate and FC Pessimistic). Categories range from species that have not lost distribution (0%) to species that have become extinct (100%).

Scenario	0%	< 25%	25–50%	50–75%	75–100%	100%
Climate change only						
Optimistic	13	120	57	36	29	3
Intermediate	12	109	56	36	41	5
Pessimistic	13	95	57	37	53	7
Climate and land use change						
Baseline Optimistic	3	14	60	109	59	3
Baseline Intermediate	3	14	57	104	67	6
Baseline Pessimistic	3	14	50	99	79	8
FC Optimistic	3	22	80	91	49	3
FC Intermediate	3	22	72	87	61	6
FC Pessimistic	3	21	66	79	76	8

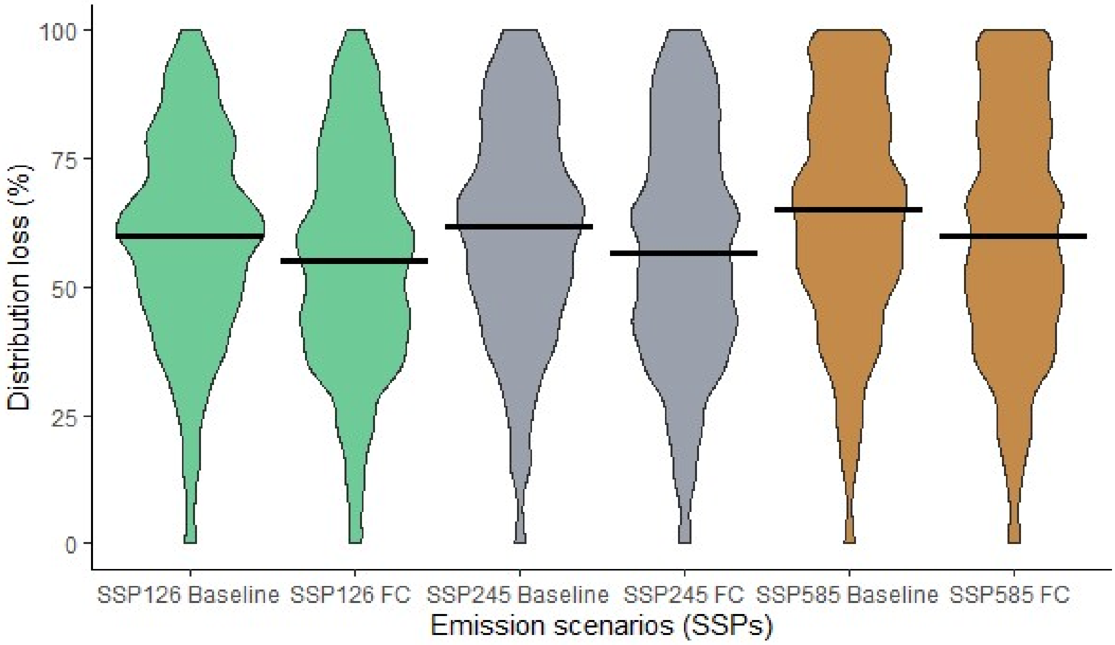

Figure 4: Percentage of species distribution loss under different emission scenarios and land use change associated with forest code. The black line is the average loss.

When considering the full implementation of the forest code, there was a reduction in species loss for 2050. In the optimistic baseline, species will lose an average of 55% (±22%), increasing to 57% (±23%) and 60% (±24%) in the intermediate and pessimistic baseline scenarios, respectively (Figure 4). However, although all land use scenarios reduce distribution loss for most species, the fully implemented forest code (FC scenario) reduces distribution loss compared to the baseline scenario (Figure 5).

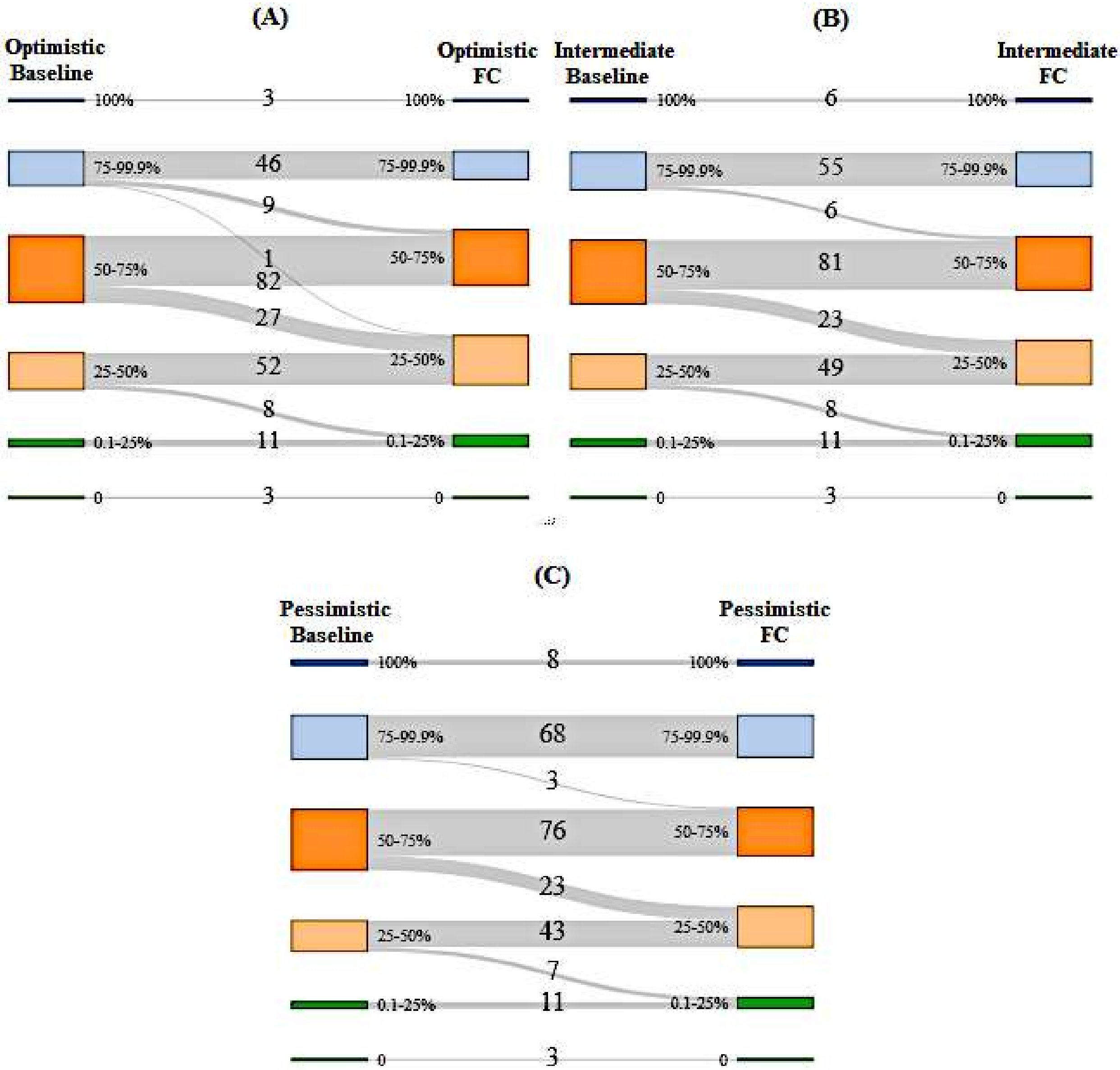

Figure 5: Comparison of the species number in each loss distribution category between the baseline and FC scenario (full implementation of the forest code) in 2050, considering (A) optimistic, (B) intermediate, and (C) pessimistic climate change scenarios.

Also, considering the land use change associated with FC scenarios, species will occur mainly in the southeastern and central regions of the Cerrado biome (Figure 6). There was an increase in distributional losses and, consequently, richness loss when the effects of the climate and land use scenarios were evaluated together. Therefore, the southern, southeastern, and central locations are projected to be areas of greatest net reductions in species richness under climate change scenarios, as these regions are where species richness is currently greatest. The SSP585 estimated a larger loss distribution loss than SSP245 in both the baseline scenario and FC. However, compared to the other scenarios, species losses are reduced with forest code implementation (Figure 7).

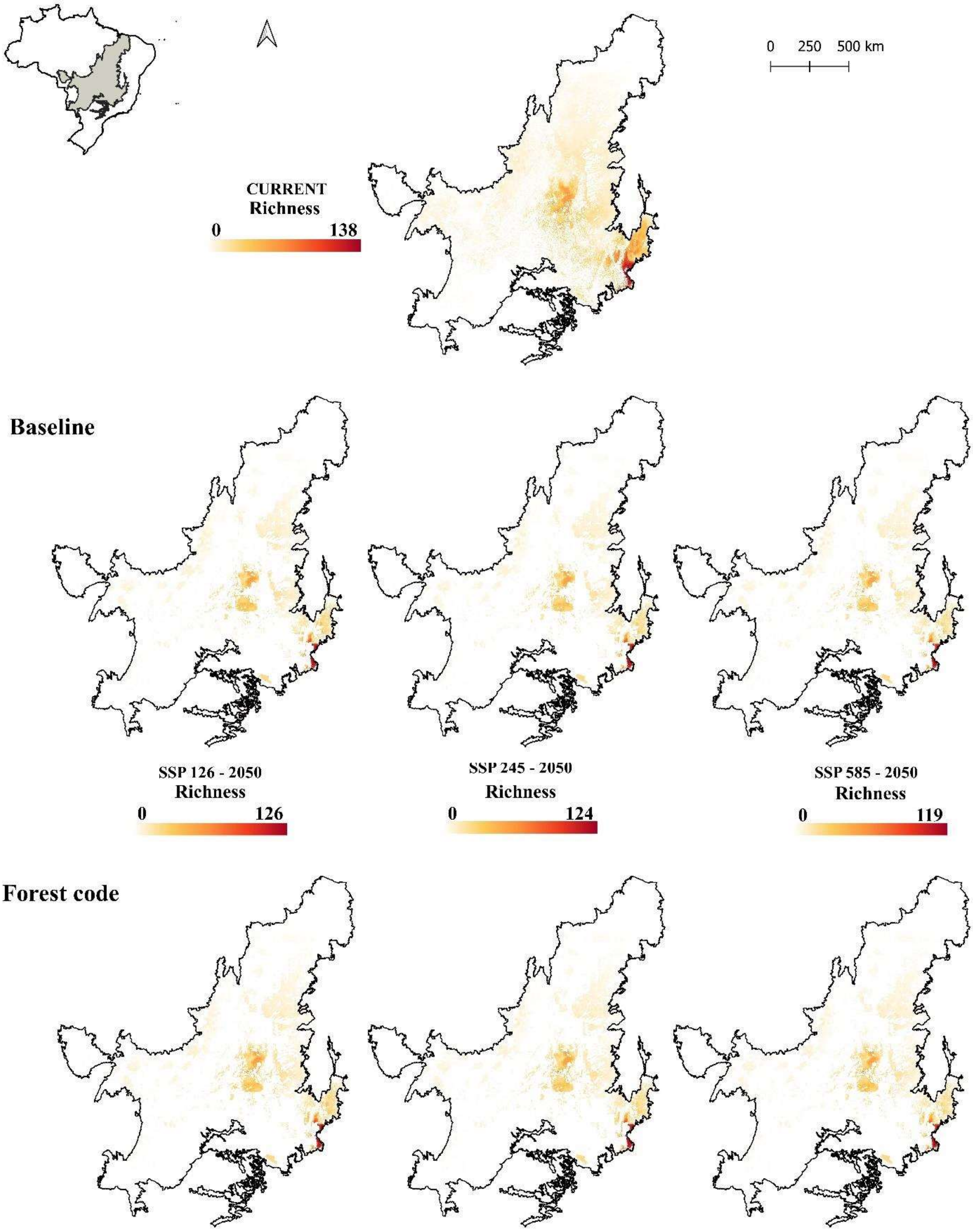

Figure 6: Richness of Cerrado endemic and endangered species for current and future emission scenarios and associated with land use change scenarios related to implementing forest code (2050).

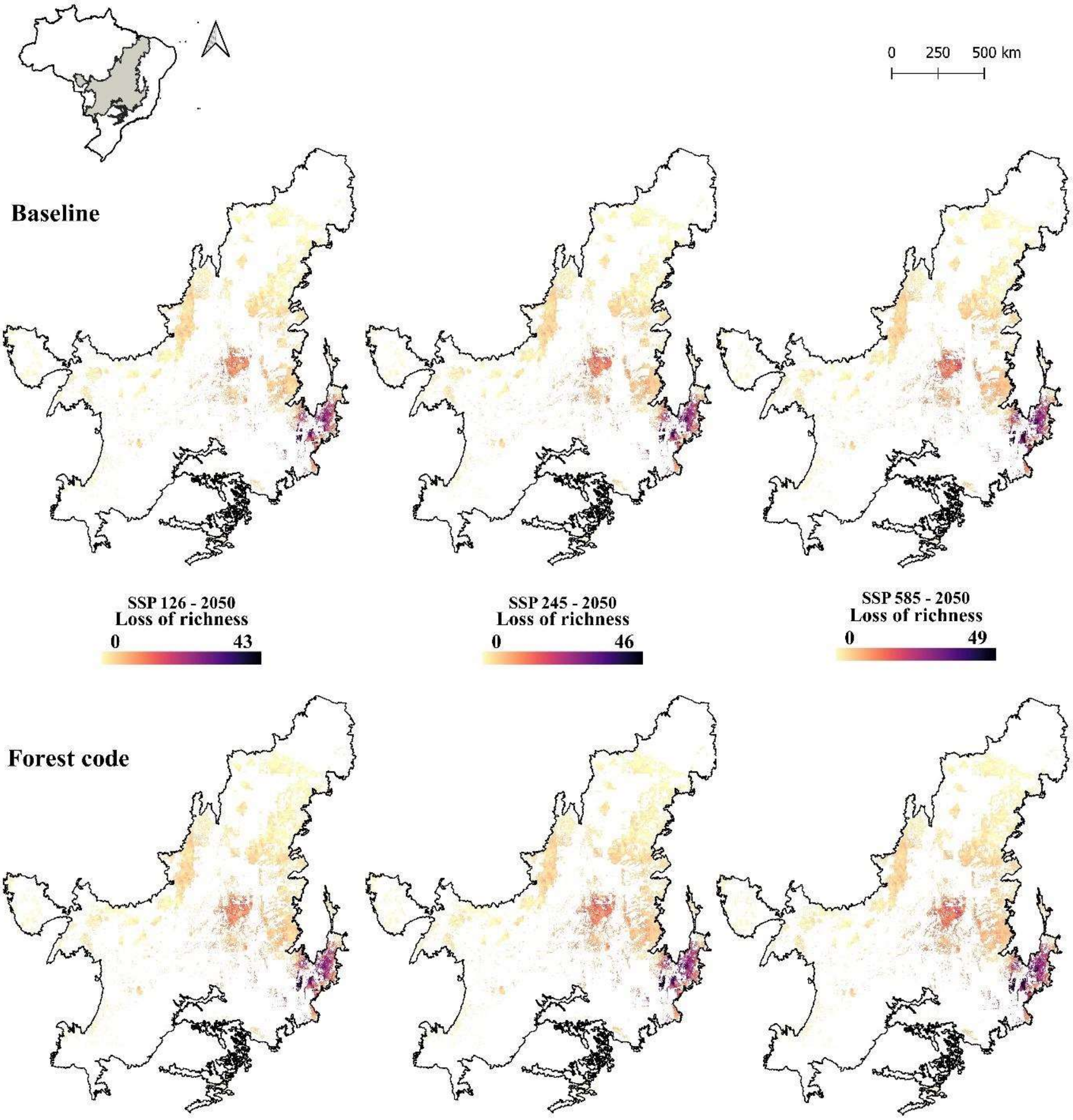

Figure 7: Richness loss of Cerrado endemic and endangered species for current and future emission scenarios and associated with forest code (2050).

Discussion

Here we used species distribution models to evaluate the impacts of climate, and land use change related to national environmental policies enforcement on the distribution of endemic and threatened plant species in Brazillian Cerrado. Our findings predict that climate and land use change will drastically reduce the geographical distribution of most species by 2050, with more significant losses in regions with the greatest species richness. Even in the optimistic climate scenario (i.e., SSP126) with full implementation of forest code (no illegal deforestation and restoration), about 89% of species will lose >30% of their range. These predictions get even worst if flexibilization of forest code implementation is allowed. Considering that these species are already threatened, more species will probably be in a more severe category of extinction risk in the future.

Climate and land use impact biodiversity. Several papers predicting these impacts will be especially drastic for plants in hotspot areas because many species in these regions are rare and more susceptible to extinction with the threat caused by human impact and intense loss of natural cover (JÚNIOR; PEREIRA, 2017; SAWYER *et al*., 2018; BOZELLI *et al*., 2018; COSTA-COUTINHO *et al*.,2019). Thus, the combined evaluation of the impact of both processes on biodiversity is highly relevant to allow the delineation of conservation strategies to mitigate them and ensure the effective conservation of species (ENQUIST *et al*., 2019). Adopting environmental health policies aiming to protect and restore degraded ecosystems can reduce plant extinction rates (LE ROUX *et al*., 2019).

Climate alone was responsible for a 41% loss in the pessimistic scenario. This is consistent with several works worldwide predicting climate impacts on species distribution (DA SILVA *et al*., 2019; HANNAH *et al*., 2020; MANES *et al*., 2021), especially the same occurs for plants in the Cerrado (VELAZCO *et al.,* 2018). We showed that the threatened and endemic species of the Brazilian Cerrado would become more vulnerable to extinction in response to climate change, and the possible consequences should not be neglected at the ecosystem level. Studies on Cerrado pointed to climate variables as responsible for determining vegetation distribution (SOLÓRZANO 2011). Changes in climate can rapidly modify the present climatically suitable areas for species (LOARIE *et al*. 2009), since plants are a group that have their distribution patterns altered with climate (ARAÚJO; PEARSON, 2005).

Tropical lowland regions are predicted to experience more rapid climate change, with increasing temperature, decreasing precipitation (COLWELL *et al*., 2008; VASCONCELOS; DO NASCIMENTO, 2016), and the hottest and driest conditions ever analyzed in recent decades that may cause an imminent collapse in the biome (HOFMANN *et al*., 2021).

Our results emphasize that in the Cerrado, the southern and southeastern regions are areas of higher concentration of species in the present and in the future, which is consistent with other research on the Cerrado flora (SIMON *et al.,* 2013; VELAZCO *et al.,* 2018) and fauna (DINIZ-FILHO *et al.,* 2009). Although these areas can be considered refugia for the species, it is essential to highlight that the natural cover of these regions was lost and is intensely fragmented (SANO *et al*., 2010; STRASSBURG *et al*., 2017). Consequently, actual land use conditions may imperil species persistence in the future (LOYOLA *et al*., 2012). In addition, conservation of rare species, for example, should be based on the conservation of habitats where these most vulnerable species have occurrence (GENG *et al*., 2012) because even with restoration of areas, accounted for in the forest code land use scenario, many species cannot recolonize these areas immediately (BROCK *et al*., 2021).

Land use change further accentuated the loss of species distribution. All scenarios, including land use, have generated large losses. Habitat loss is considered the leading cause of extinction in the world (CIPULLO, 2016). Due to land use changes plant populations are destroyed or displaced, reduce abundance and richness, generates fragmentation of natural areas, intraspecific and interspecific interaction (SILVA: BARBOSA, 2019). The cerrado has experienced an increase in deforestation in recent years, greater than the other Brazilian biomes. This deforestation pressure occurs mainly due to agricultural expansion. Brazil is an important food supplier worldwide, and Cerrado was associated with large government projects of agricultural modernization (ESPERA, 2017; PIRES, 2020.). The expansion of the agricultural frontier is associated with irreparable environmental impacts with transformation of natural landscapes and species extinction. Despite policies to stop deforestation in the Cerrado region, land use data show that this region continues to lose its natural cover (Mapbiomas Brasil, http://mapbiomas.org/). Pessimistic projections point to an increase of 19% in deforestation in the Cerrado, leading to a loss of 60% of native vegetation.

The land use scenarios used here show the effect of different provisions of the forest code, imposing or relaxing restrictions on land use transitions. Although species distribution loss will be intensified in all land use change scenarios, full implementation of the forest code reduces species distribution loss (BROCK *et al*., 2021). A full compliance with the forest code offers protection to biodiversity, and works highlight the importance of developing a policy mix that creates incentives for sustainable land use practices because the Cerrado will be affected and the landowners with agriculture and cattle ranching have a prospect of economic loss the forest code (SOARES FILHO *et al*. 2006; BIRD et al. 2012; STRASSBURG *et al*. 2012; DE CASTRO SOLAR *et al*. 2016; AZEVEDO *et al*., 2017;). However, the forest code points out that environmental reserves coupled with the strategic expansion of protected areas on private and public lands can contribute to rescuing the Cerrado since the biome will be the most disturbed (VIEIRA *et al.*, 2017). However, actions only with the implementation of the forest code may not be sufficient or achievable under conservation plans. The Brazilian forest code aims to regulate deforestation on private lands, but it was recently shown that the areas considered legal for deforestation are much larger deforestation are much larger than those that would have to be restored. Despite the advances, the current code has many flaws, such as regulations that have reduced or even eliminated the obligation to protect certain areas previously protected by the old forest code of 1965 and which are of environmental importance. (BRANCALOIN *et al.*, 2016).

Although the forest code considers restoration to be the recolonization of restored areas, this may not happen. The recolonization of degraded areas has difficulties on a landscape scale, along with sustainable management of other types of land use, including agriculture, grazing, forestry, expansion, and consolidation of protected areas, is an essential activity for biodiversity conservation (JANISHEVISK *et al.*, 2015). Thus, anthropic intervention in global climate, nutrient cycling, and species displacement has propitiated the understanding that biodiversity is involved in the socioeconomic system with social and political relationships (JUNIOR; PEREIRA, 2017). The forest code is designed to help mitigate the consequences of climate change and achieve various goals such as biodiversity conservation, climate change mitigation, and sustainable development goals. Thus, our results corroborates that a full implementation of the forest code, can benefit biodiversity by mitigating species habitat loss, thus contributing to biodiversity conservation in the Cerrado (BROCK *et al.*, 2021).

Although the forest code is projected to be fully and effectively implemented, it is expected that many species will lose a significant area of their natural habitat (BROCK *et al.*, 2021). Thus, implementation of the forest code should be complemented with other conservation strategies, such as the creation of protected areas and ecological corridors, and effective restoration projects (PEREIRA; CESTARO, 2016; DE ARAÚJO; DE HOLANDA BASTOS, 2019). Vegetation cover, even if in small portions of fragments, can increase connectivity and promote the persistence of species, increasing the ability to colonize new areas that have suitable climatic conditions for the occurrence of species, facilitating the adaptive response of organisms to climate change in anthropized landscapes (MANNING *et al.*, 2009). Thus, it is possible to carry out actions for the creation of conservation or restoration units in areas of climatic refugia in the Cerrado (TÔRRES *et al.*, 2012).

Models and scenarios are critical to guide the development and implementation of public policy together other land use policies. The results of the loss of Cerrado endemic and endangered species richness for current and future emission scenarios and associated with the forest code can help in conservation planning for these species but also provide background for the need for immediate and unrestricted implementation of the forest code (BROCK *et al.*, 2021). Our climate results associated with land use are useful for helping to identify whether the areas are favorable for the species in the future under the different scenarios of forest code implementation.

Conclusão

Mudanças no clima e no uso do solo podem causar grandes danos à flora do Cerrado brasileiro, mesmo sob os cenários mais otimistas de mudança climáticas associadas a implementação do código florestal. As regiões com maiores perdas de diversidade são regiões com maior riqueza de espécies e consequentemente a conservação da flora será drasticamente afetada com a diminuição das ocorrências das espécies. Mesmo com a implementação do código florestal é esperado perdas consideráveis da distribuição das espécies causadas pela mudança climáticas e uso do solo, com isso espécies que já são endêmicas e ameaçadas poderão se extinguir. Projetos de conservação e restauração de habitats juntamente com a plena e efetiva implementação do código florestal serão necessários para auxiliar a proteção das espécies do Cerrado.

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Supporting Information

FIGURES

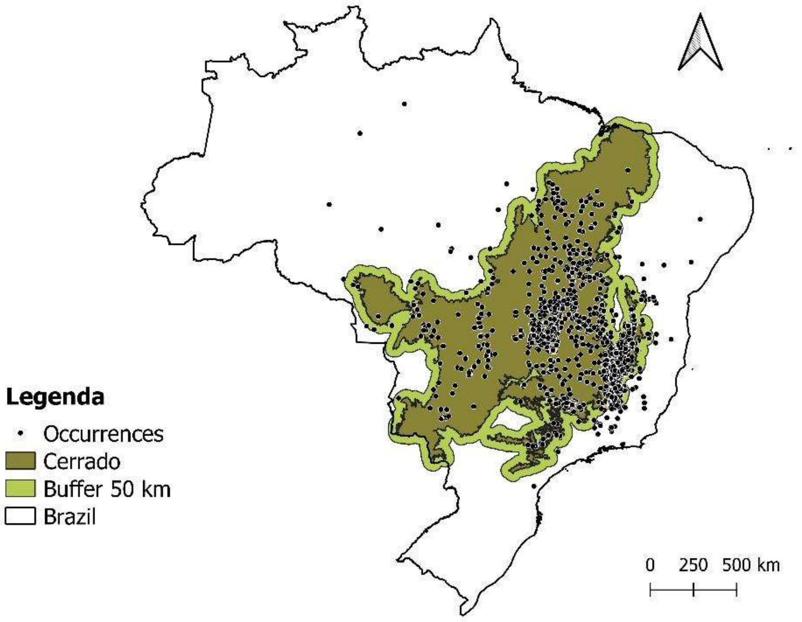

Figure S1: Brazilian Cerrado boundaries with 50 km buffer and the occurrence data of 242 species.

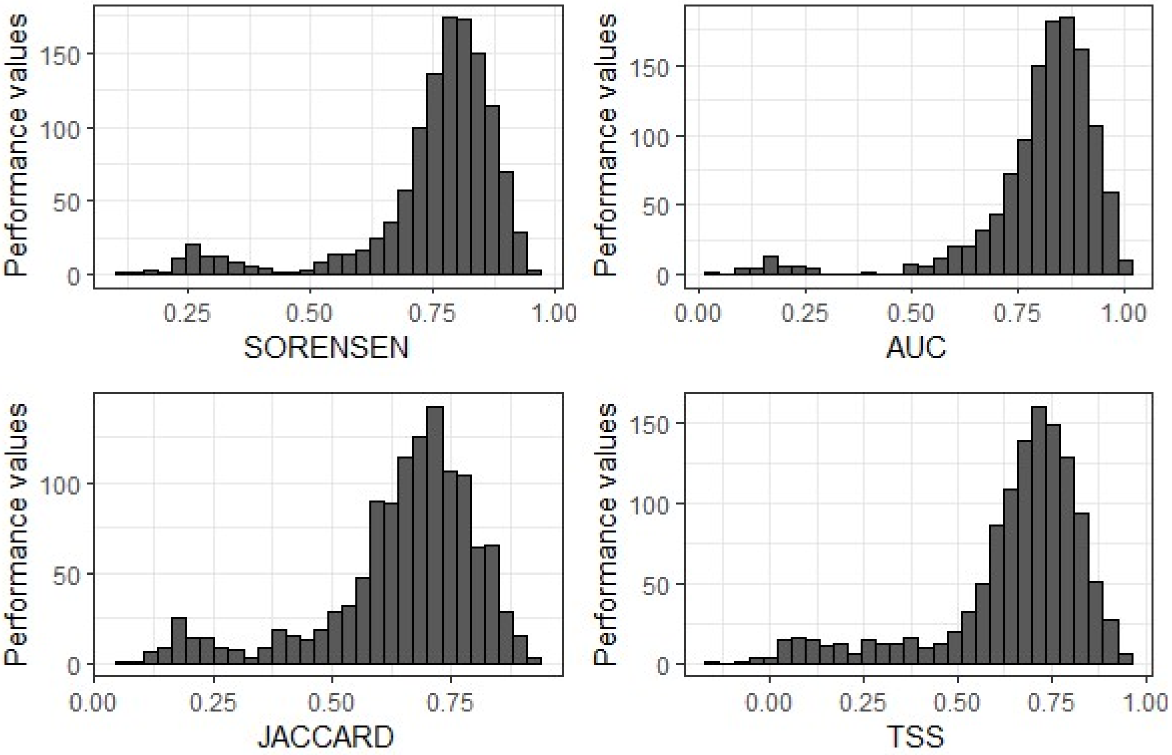

Figure S2: Mean model performance metrics Sorensen, AUC, Jaccard, and TSS for all 242 Cerrado endemic species together based on Generalized Linear Models (GLM), Generalized Boosted Regression (GBM), Maximum Entropy (MaxEnt), Generalized Additive Models (GAM), and Neural Network Algorithms (NET).

TABLES

Table S1. Threshold values at which the sum of sensitivity and specificity is the highest for each species.

Species	Threshold	Species	Threshold
Actinocephalus cipoensis	0.115	*Lychnocephalus sellovii*	0.029
Actinocephalus claussenianus	0.084	*Lychnocephalus tomentosus*	0.196
Agalinis brachyphylla	0.178	*Lychnophora diamantinana*	0.291
Alcantarea duarteana	0.081	*Lychnophora gardneri*	0.068
Aldama filifolia	0.13	*Lychnophora martiana*	0.117
Anteremanthus hatschbachii	0.099	*Lychnophora pohlii*	0.024
Aspilia cylindrocephala	0.169	*Lychnophora rupestris*	0.193
Aspilia diffusiflora	0.128	*Lychnophora souzae*	0.097
Aspilia ovatifolia	0.147	*Lychnophora staavioides*	0.118
Attalea barreirensis	0.173	*Lychnophora villosissima*	0.172
Baccharis concinna	0.209	*Marcetia hatschbachii*	0.196
Baccharis elliptica	0.249	*Marcetia semiriana*	0.092
Banisteriopsis andersonii	0.087	*Merianthera eburnea*	0.147
Banisteriopsis arborea	0.264	*Merianthera sipolisii*	0.107
Banisteriopsis cipoensis	0.17	*Miconia angelana*	0.132
Banisteriopsis hatschbachii	0.402	*Miconia cipoensis*	0.159
Banisteriopsis hirsuta	0.009	*Micranthocereus albicephalus*	0.216
Barbacenia delicatula	0.172	*Micranthocereus auriazureus*	0.254
Barbacenia longiscapa	0.195	*Micranthocereus violaciflorus*	0.202
Bernardia crassifolia	0.166	*Microlicia canastrensis*	0.16
Bursera pereirae	0.12	*Microlicia psammophila*	0.102
Butia capitata	0.118	*Mikania cipoensis*	0.058
Byrsonima cipoensis	0.089	*Mikania glabra*	0.199
Byrsonima fonsecae	0.238	*Mikania hartbergii*	0.228
Byrsonima martiana	0.153	*Mikania itambana*	0.184
Byrsonima spinensis	0.02	*Mikania neurocaula*	0.165
Calea abbreviata	0.143	*Mikania premnifolia*	0.416
Calea heteropappa	0.152	*Mimosa adamantina*	0.073
Calliandra carrascana	0.086	*Mimosa barretoi*	0.136
Callisthene erythroclada	0.137	*Mimosa decorticans*	0.301
Camarea humifusa	0.229	*Mimosa rheiptera*	0.021
Camarea linearifolia	0.134	*Minaria grazielae*	0.011
Cambessedesia atropurpurea	0.185	*Minaria polygaloides*	0.214
Canastra lanceolata	0.123	*Minaria refractifolia*	0.131
Cattleya ghillanyi	0.193	*Minasia alpestris*	0.299
Cereus mirabella	0.108	*Minasia pereirae*	0.133
Chamaecrista bracteolata	0.107	*Minasia scapigera*	-0.002

Chamaecrista fodinarum	0.16	*Monteverdia chapadensis*	0.055
Chamaecrista fulgida	0.183	*Monteverdia rupestris*	0.097
Chamaecrista lagotois	0.086	*Moquilea araneosa*	0.121
Chamaecrista phyllostachya	0.11	*Moquiniastrum hatschbachii*	0.089
Chamaecrista stillifera	0.188	*Ormopteris cymbiformis*	0.266
Chamaecrista tephrosiifolia	0.11	*Ormopteris gleichenioides*	0.055
Chamaecrista ulmea	0.221	*Oxypetalum ekblomii*	0.151
Chresta souzae	0.26	*Paepalanthus echinoides*	0.291
Chromolaena arrayana	0.187	*Paepalanthus macer*	0.059
Chronopappus bifrons	0.094	*Paepalanthus polygonus*	0.094
Cinnamomum quadrangulum	0.083	*Paepalanthus urbanianus*	0.432
Cipocereus bradei	0.145	*Paspalum longiaristatum*	0.181
Cipocereus crassisepalus	0.255	*Pavonia grazielae*	0.155
Cissus inundata	0.195	*Peixotoa cipoana*	0.295
Cleistes aphylla	0.125	*Peixotoa psilophylla*	0.283
Clusia burchellii	0.075	*Persea fusca*	0.153
Clusia diamantina	0.14	*Pilosocereus aurisetus*	0.159
Comanthera elegans	0.019	*Pilosocereus fulvilanatus*	0.204
Cuphea adenophylla	0.157	*Piptolepis buxoides*	0.146
Cuphea teleandra	0.029	*Piptolepis imbricata*	0.161
Cyanocephalus caprariifolius	0.206	*Piptolepis leptospermoides*	0.122
Cyanocephalus digitatus	0.045	*Pitcairnia bradei*	0.079
Cyrtopodium triste	0.165	*Pleroma integerrimum*	0.292
Didymopanax gardneri	0.134	*Pleroma wurdackianum*	0.584
Didymopanax glaziovii	0.139	*Plinia espinhacensis*	0.594
Didymopanax villosissimus	0.199	*Podocarpus barretoi*	0.241
Dimerostemma grazielae	0.039	*Polygala franchetii*	0.537
Diplusodon aggregatifolius	0.184	*Polygala stephaniana*	0.379
Diplusodon gracilis	0.016	*Pombalia strigoides*	0.613
Diplusodon minasensis	0.047	*Proteopsis argentea*	0.438
Diplusodon orbicularis	0.066	*Pseudotrimezia subtilis*	0.509
Diplusodon ovatus	0.104	*Pseudotrimezia synandra*	0.562
Distimake repens	0.194	*Psidium sessiliflorum*	0.274
Disynaphia praeficta	0.098	*Pterodon apparicioi*	0.665
Drosera graminifolia	-0.009	*Qualea hannekesaskiarum*	0.336
Drosera graomogolensis	0.214	*Qualea lundii*	0.326
Duguetia rotundifolia	0.03	*Richterago angustifolia*	0.521
Echinocoryne echinocephala	0.075	*Richterago arenaria*	0.56
Encholirium disjunctum	0.068	*Richterago caulescens*	0.296
Encholirium heloisae	0.111	*Richterago conduplicata*	0.466
Encholirium luxor	0.198	*Richterago elegans*	0.685

Eremanthus argenteus	0.041	*Richterago hatschbachii*	0.392
Eremanthus reticulatus	0.029	*Richterago lanata*	0.705
Eremanthus veadeiroensis	0.13	*Richterago petiolata*	0.349
Eriotheca parvifolia	0.156	*Richterago polyphylla*	0.598
Esenbeckia irwiniana	0.1	*Richterago riparia*	0.533
Esenbeckia oligantha	0.212	*Richterago stenophylla*	0.587
Esterhazya caesarea	0.185	*Rudgea obtusa*	0.271
Eugenia hatschbachii	0.2	*Sphaerorrhiza burchellii*	0.484
Evolvulus rariflorus	0.133	*Spigelia lundiana*	0.461
Evolvulus riedelii	0.16	*Sporobolus apiculatus*	0.699
Gaylussacia oleifolia	0.148	*Stachytarpheta procumbens*	0.459
Goyazia petraea	0.321	*Staurogyne elegans*	0.583
Gymnopogon doellii	0.162	*Stenandrium hatschbachii*	0.387
Heterocoma albida	0.092	*Stevia hilarii*	0.487
Heterocoma ekmaniana	0.191	*Strophopappus ferrugineus*	0.273
Heterocoma lanuginosa	0.015	*Styrax aureus*	0.509
Homalolepis salubris	0.186	*Syagrus glaucescens*	0.224
Homalolepis warmingiana	0.15	*Symphyopappus uncinatus*	0.565
Huberia piranii	0.084	*Symplocos glaberrima*	0.576
Hypenia aristulata	0.322	*Tococa macroptera*	0.474
Hypenia micrantha	0.187	*Trembleya chamissoana*	0.279
Hyptidendron conspersum	0.127	*Trembleya hatschbachii*	0.478
Hyptidendron leucophyllum	0.011	*Trimezia exillima*	0.516
Hyptis arenaria	0.179	*Uebelmannia gummifera*	0.592
Hyptis cruciformis	0.059	*Uebelmannia pectinifera*	0.642
Hyptis frondosa	0.055	*Vellozia glabra*	0.615
Hyptis hamatidens	0.181	*Vellozia hatschbachii*	0.2
Hyptis imbricatiformis	0.075	*Vellozia metzgerae*	0.559
Hyptis penaeoides	0.209	*Vellozia patens*	0.358
Ichthyothere elliptica	0.279	*Virola urbaniana*	0.819
Klotzschia rhizophylla	0.099	*Vochysia pygmaea*	0.511
Lagenocarpus bracteosus	0.245	*Vochysia rotundifolia*	0.458
Lavoisiera cordata	0.145	*Vriesea diamantinensis*	0.508
Leiothrix echinocephala	0.106	*Waltheria polyantha*	0.508
Lepidaploa spixiana	0.141	*Wedelia macedoi*	0.347
Lessingianthus eitenii	0.167	*Wunderlichia senae*	0.473
Lessingianthus irwinii	0.352	*Xyris aurea*	0.368
Lessingianthus souzae	0.184	*Xyris blepharophylla*	0.585
Lessingianthus stoechas	0.047	*Xyris cipoensis*	0.335
Lessingianthus venosissimus	0.22	*Xyris hystrix*	0.383
Lessingianthus zuccarinianus	0.056	*Xyris platystachya*	0.397

Luxemburgia angustifolia	0.142	*Xyris sincorana*	0.492
Lychnocephalus mellobarretoi	0.145	*Zephyranthes irwiniana*	0.483

Table S2. Climate and edaphic variables used for PCA.

Source	Variables
WorldClim	Annual mean temperature (BIO1) Mean diurnal range (BIO2) Isothermality (BIO3) Temperature Seasonality (BIO4) Max temperature of warmest month (BIO5) Min temperature of coldest month (BIO6) Temperature annual range (BIO7) Mean temperature of wettest quarter (BIO8) Mean temperature of driest quarter (BIO9) Mean temperature of warmest quarter (BIO10) Mean temperature of coldest quarter (BIO11) Annual precipitation (BIO12) Precipitation of wettest week (BIO13) Precipitation of driest week (BIO14) Precipitation seasonality (BIO15) Precipitation of wettest quarter (BIO16) Precipitation of driest quarter (BIO17) Precipitation of warmest quarter (BIO18) Precipitation of coldest quarter (BIO19)
SoilGrids	Bulk density* Coarse fragments* Clay* Sand* Silt*

*Data for six depths (0-5centimeter, 5-15centimeter, 15-30centimeter, 30-60centimeter, 60-100centimeter, 100-200centimeter)

Table S3. The cumulative variance explained for each PCA axis.

Axis – Principal Components (PC)	**Cumulative Variance - PCA**
PC1	0.38935
PC2	0.57212
PC3	0.72611
PC4	0.8084
PC5	0.87624
PC6	0.90971
PC7	0.93243
PC8	0.94931
PC9	0.96361
PC10	0.97207
PC11	0.97903
PC12	0.98427
PC13	0.98813
PC14	0.99092
PC15	0.99288
PC16	0.99419
PC17	0.99532
PC18	0.99607
PC19	0.99673
PC20	0.99715
PC21	0.99753
PC22	0.99783
PC23	0.99811
PC24	0.99838
PC25	0.99862
PC26	0.99884
PC27	0.99903
PC28	0.99915
PC29	0.99926
PC30	0.99937
PC31	0.99947
PC32	0.99956
PC33	0.99964
PC34	0.99971
PC35	0.99977
PC36	0.99983
PC37	0.99988
PC38	0.99992
PC39	0.99996
PC40	0.99999
PC41	1

PC42	1
PC43	1
PC44	1
PC45	1
PC46	1
PC47	1
PC48	1
PC49	1