Contents lists available at ScienceDirect

Perspectives in Ecology and Conservation

journal homepage: www.perspectecolconserv.com

Research Letters

Climate change and feeble governance threaten the endangered endemic Cerrado flora in Brazil

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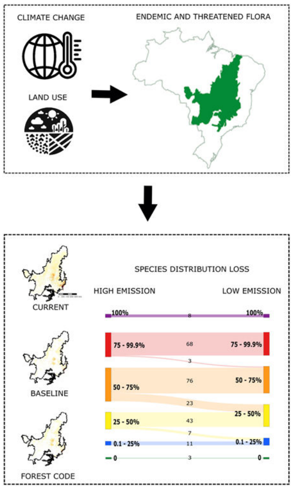
HIGHLIGHTS

- Projections indicate significant species range reductions by 2050, even under optimistic climate scenarios.
- The interaction between land-use and climate change leads to compounded impacts on the threaten the endemic Cerrado flora.
- Partial implementation of the Forest Code leads higher biodiversity loss in the Cerrado.
- Despite Forest Code safeguards, complementary measures are essential to secure Cerrado biodiversity.
- Conservation plans must address both climate change impacts and land-use dynamics to preserve the ecological integrity of the Cerrado.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Neotropical savanna
Climate change
Species distribution models

ABSTRACT

Cerrado biome, home of many plants endemic species, is suffering significant habitat loss due to anthropic actions, including natural cover loss and climate change. Here we assess how climate change and future natural cover loss will impact the distribution of endemic and threatened flora in the Cerrado, considering two scenarios related to the implementation of Brazil's Forest Code: the baseline scenario (BS), which reflects partial

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https://doi.org/10.1016/j.pecon.2025.08.007
Received 18 June 2024; Accepted 30 August 2025

Please cite this article as: Emilly Layne Martins do Nascimento et al., , https://doi.org/10.1016/j.pecon.2025.08.007

Natural cover loss
Brazilian forest code
Threatened species

implementation, and the full implementation of Brazil's Forest Code (IFC). By 2050, distribution losses are projected at 33% under the SSP126 scenario, increasing to 37% and 41% under the SSP245 and SSP585 scenarios, respectively. Species are likely to retreat to the southern, southeastern, and central regions, which are the richest in species but will face the most severe reductions. Despite the IFC scenario offering better protection, nearly all species (239) will still experience distribution reductions, even under the most favorable scenarios in this analysis. The study confirms that both climate and natural cover loss will significantly diminish the geographical range of most species by 2050, particularly in areas with the highest current richness. This trend could lead to increased extinction risks, which could be reduced with the full implementation of the Forest Code.

Introduction

Climate and land-use changes are major drivers of biodiversity loss. While impacts on climate and land use can individually impact biodiversity, their combined effects are even more devastating and play a significant role in the biodiversity crisis. Therefore, predictions regarding the concomitant impacts of climate change and land use on biodiversity are crucial due to the complex nature of their combined consequences (He et al., 2019).

Human influence on climate has been evident and unprecedented in recent years. The predicted increase in global temperature for the coming decades exceeds the average recorded during the entire Holocene (IPCC, 2023). Climate change significantly impacts ecosystems and threatens biodiversity as it can cause changes in species distribution and potentially lead them to extinction (Cahill et al., 2013). Although climate change is the main studied factor affecting biodiversity, land-use changes and natural cover loss due to agricultural expansion and urbanization are the leading causes of biodiversity extinction in most ecosystems (Caro et al., 2022). Land-use change directly impacts flora extinction worldwide (Nic Lughadha et al., 2020). Global change scenarios predict that natural cover loss and climate change will intensify by the end of the century, leading to the potential extinction of thousands of species (Oliver and Morecroft, 2014).

The Brazilian Cerrado, the second largest biome in Brazil (Damasco et al., 2018) and the world's richest savanna biome, is under severe threats due to significant native vegetation loss, with 46% already degraded (Strassburg et al., 2017; Alencar et al., 2020). Without intervention, an additional 34% could vanish by 2050, potentially causing the largest plant extinction event on record (Strassburg et al., 2017). The combined effect of climate change and natural cover loss can severely impact biological diversity and lead to local plant extinctions in Cerrado (Ladwig et al., 2018). Indeed, a recent study showed that future climate change combined with land use change could affect the flora of the Cerrado, even if in optimistic scenarios (Velazco et al., 2019).

The Cerrado is home to over 12,000 plant species, 44% of which are endemic to the region (Damasco et al., 2018). Endemic species, which generally have restricted distributions and small population sizes, are particularly vulnerable to environmental changes. Their limited range, combined with insufficient coverage by conservation units, increases their risk of extinction (Cahill et al., 2013; Manes et al., 2021). As a result, endemic and threatened species are at high risk of disappearing soon, thereby requiring urgent conservation actions. The disappearance of endemic and threatened species could lead to disproportionate impacts on ecosystem dynamics, as many plays essential roles in maintaining pollination and seed dispersal networks, regulating microclimates, and stabilizing soils. Thus, this species can serve as indicators of the potential ecological consequences of biodiversity loss in the Cerrado.

Global trends show increasing land-use change and natural cover loss, yet robust environmental policies like the Brazilian Forest Code (FC), revised in 2012, can effectively enhance habitat protection, promote restoration efforts, reduce greenhouse gas (GHG) emissions and safeguard biodiversity (Tabarelli et al., 2005; Soterroni et al., 2018; Brock et al., 2021). The FC regulates land use on private properties to balance conservation with agricultural expansion, helping prevent illegal native vegetation losses (hereafter also referred to as 'deforestation') and fostering its recovery. Illegal deforestation refers to the unauthorized clearance or removal of native vegetation in violation of environmental regulations, a major driver of habitat loss in Brazil.

The FC plays a key role in facilitating significant emission reductions, aiding Brazil in meeting its short-term Paris Agreement targets (Soterroni et al., 2023). Furthermore, the FC supports biodiversity by reducing habitat loss for various species and enabling restoration, which allows species to regain previously unavailable habitats (Brock et al., 2021). Despite its potential, the law's full implementation across all Brazilian biomes remains challenging, which limits its effectiveness in meeting conservation and climate goals (Soares-Filho et al., 1979; CPI, 2023).

Although Brazil's Forest Code has relatively low requirements for native vegetation protection on rural properties in the Cerrado (20–35%), compared to the Amazon (80%), and is often considered insufficient to safeguard the biome (Chaves et al., 2023; da Conceição Bispo et al., 2024; Pereira et al., 2024), its absence would significantly exacerbate biodiversity loss in this already highly threatened region. Without the Forest Code implementation, the remaining 57% of the Cerrado's vegetation could be reduced to just 13% (Metzger et al., 2019), underscoring the critical need to fully enforce this legislation. Considering the threats faced by the Cerrado flora and the importance of FC as a key public policy to native vegetation protection, it is crucial to assess whether the implementation of the FC, either partially or fully, can effectively help to mitigate the potential impacts of land use and climate change on the biodiversity of this biome. Hence, here 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 FC can contribute to mitigating its consequences.

Methods

Study area, species assessed, and occurrence data

The study area focused on the Brazilian Cerrado biome as delimited by Instituto Brasileiro de Geografia e Estatística (IBGE, 2005). Initially, we obtained the National List of Endangered Species - Flora by Conabio Resolution 08/2021 (CONABIO, 2022). We used National Center for the Conservation of Flora (http://www.cncflora.jbrj.gov.br/portal) as source of Cerrado species endemism. Our selection comprised 542 endemic and endangered species. Species occurrences were obtained from the following sources: Global Biodiversity Information Facility, Botanical Information and Ecological Network, Integrated Digitized Biocollections, SpeciesLink network, Brazilian Biodiversity Information System, Portal da Biodiversidade, and Tree Flora of the Neotropical Region (Table S1). Occurrence data resulted from work of BDC (Biodiversity Data Cleaning) package with Brazil's terrestrial plants (Ribeiro et al., 2022). The data clean process involved merging the occurrence datasets and checking and rectifying taxonomic, spatial, and temporal inconsistencies. Taxonomic cleaning entailed syntactic analysis and harmonization of scientific names based on taxonomic groups. Spatial cleaning addressed the removal of erroneous, suspicious, and duplicate occurrences, while temporal cleaning corrected inconsistencies in collection dates (Ribeiro et al., 2022).

To assess species endemism in the Cerrado, we established a 50 km buffer around its border (Figure S1), allowing for the identification of species considered endemic but found in other biomes, due to outdated assessments that do not account for recent records. Species were classified as endemic based on whether 70% or 90% of their occurrences were within this buffer, for species with fewer than 10 and more than 10 occurrences, respectively. Species not meeting these criteria were excluded. We then sampled one occurrence per 10 km^2 grid cell using the ENMTML package to correct spatial biases (Andrade et al., 2020), and only included species with at least six unique occurrences to ensure reliable model generation (Breiner et al., 2018). We analyzed 3,794 occurrence records for 242 species (Table S2).

Climate and edaphic data

We constructed species distribution models using 49 bioclimatic and edaphic variables. Climate data were sourced from the WorldClim v2.1 database (https://www.worldclim.org/), providing 19 bioclimatic variables for the periods 1970–2000 and 2050 across three emission scenarios (SSP 126, SSP 245, SSP 585) using eight Atmosphere-Ocean General Circulation Models (BCC-CSM2-MR, CNRM-CM6-1, CNRM-ESM2-1, CanESM5, GFDL-ESM4, IPSL-CM6A-LR, MIROC-ES2L, MIROC6, MRI-ESM2-0), at a 10 km resolution.

We considered three Shared Socioeconomic Pathways (SSPs) to project future climate conditions: SSP1-2.6, SSP2-4.5, and SSP5-8.5. These scenarios represent different trajectories of greenhouse gas emissions and socioeconomic development. SSP1-2.6 describes a sustainable pathway with low emissions, assuming rapid global decarbonization and strong environmental policies. SSP2-4.5 represents a moderate scenario with intermediate emissions, reflecting a balance between fossil fuel dependence and renewable energy adoption. SSP5-8.5 corresponds to a high-emission scenario with continued reliance on fossil fuels, leading to significant global warming.

Edaphic data included five physical properties at six depths from the SoilGrids (https://soilgrids.org/) at 270 m resolution, standardized to approximately 10 km^2 using the terra R package (Bivand et al., 2024; See Table S3 and edaphic variables section in SM). Inclusion of both climatic and edaphic variables is known to enhance the performance of plant species distribution model and improve the reliability of future projection (Velazco et al., 2017).

To tackle collinearity and reduce variables, a principal component analysis (PCA) on current climate and edaphic data was conducted, resulting in nine principal components that explained 95% of the variance, which were then used as predictors in the models (De Marco and Nóbrega, 2018). The eigenvectors from the PCA with the current conditions were used to predict scores for future scenarios, ensuring that the PCA axes remain consistent between current and future conditions.

Land use data

We used land use data from MapBiomas collection 7 (https://mapbiomas.org/) for the current period and the GLOBIOM-Brazil projections for 2050, both at a 1 km resolution (Soterroni et al., 2023; Ramos et al., 2023). We used MapBiomas for current condition because this same database is used as a base information in the processing GLOBIOM-Brazil scenarios. The GLOBIOM-Brazil model (Soterroni et al., 2018, 2019; Soterroni et al., 2023) is a regional adaptation of the GLOBIOM economic land-use model (Havlík et al., 2014), simulating land competition among agriculture, bioenergy, and forestry sectors to maximize economic welfare within resource, technological, and policy constraints, following the SSP2 pathway.

We use two land-use scenarios: baseline scenario (BS) and the full implementation of the Forest Code (IFC). These scenarios are derived from the 'Baseline' and 'FC' scenarios from Soterroni et al. (2019) downscaled to 1 km × 1 km resolution (Ramos et al., 2023). The BS scenario reflects the observed loss of native vegetation in the Amazon and Cerrado biomes during the historical period (2000–2020), when the control of illegal deforestation, as required by the Forest Code, was only partially implemented rather than fully enforced. Consequently, in addition to being the reference scenario for our analysis, the BS also represents a partial implementation of Brazil's Forest Code. The IFC scenario is built upon the BS, with the distinction that it considers the full implementation of the FC from 2020 onwards, allowing only legal deforestation and promoting nearly 12 Mha of native vegetation restoration.

Species distribution modeling

We modeled the distributions of 242 species using R software v.4.1.2 (R Core Team (2021) and the “flexsdm” package (Velazco et al., 2022). We delineated a training area for each species by creating a buffer of 100 km around the minimum convex polygon encompassing all the species' occurrence records. Pseudo-absences were randomly sampled as twice the number of presences throughout the training area.

For species with >20 occurrences (62 species) we used conventional SDM, while for species with between six to 19 occurrences (180 species), we used the Ensemble of Small Models (ESM) approach, which uses bivariate models weighted by Somers' D metric (Breiner et al., 2018) For ESMs we employed randomized data partitioning using repeated k-fold cross-validation with five folds and five replicates. For the conventional SDM we validated the models using geographic band partitioning.

The species distributions were based on the consensus predictions of the following algorithms: Generalized Linear Models (GLM), Generalized Boosted Regression (GBM), Maximum Entropy (MaxEnt), Generalized Additive Models (GAM), and Neural Networks (NET). For conventional neural network models, maximum entropy and generalized boosted regression we performed a hyperparameter tuning procedure (Table S4). We randomly sampled 10,000 background points to fit Maxent models, (Phillips et al., 2006). The treshold used to obtain threshold-dependent performance metrics was the one that maximizes the sum of sensitivity and specificity.

To address potential overprediction, we adopted a non-dispersal scenario assuming no species movement beyond current ranges. Thus, for future predictions, we only allowed species to occur in locations that were already deemed suitable in the current model within the 100 km buffer. In other words, we did not permit species to expand beyond the areas that were currently considered suitable. This non-dispersal scenario—where species are not allowed to increase their range size in the future—is based on the limited information available about the dispersal capacities of these species. By doing so, we ensure that our predictions are more conservative and realistic given the uncertainties regarding species movement.

The final models combined predictions from different algorithms, with each algorithm weighted by the Sørensen metric to reflect model performance. For future projections, we computed a weighted consensus across all AOGCMs for each emission scenario (SSP). The resulting consensus of species distribution models (SDMs) were binarized and downscaled to a 1 km resolution to align with the land-use data.

Data analysis

Impact of climate change on species

To assess the impact of climate change on species distribution, we used the binary species distribution. We developed a stacked-SDM richness map for current and future scenarios (i.e., SSPs), and calculated the difference between current and future scenarios to quantify richness turnover due to climate change.

Impact of forest code implementation scenarios on species distribution

This analysis aims to estimate the combined effects of climate and land use change on species distribution. We integrated data from Mapbiomas and GLOBIOM-Brazil scenarios, considering different FC implementation scenarios. The present land use scenario was based on Mapbiomas natural cover classes (Table S5). The binary maps of species, were overlaid with land use data, considering as suitable for species only presence sites where native vegetation covered at least 30%. The same procedure was applied for the future land use scenarios, considering only the native vegetation class from GLOBIOM. Subsequently, we generated a projected species richness map to evaluate the occurrences of species. Additionally, we produced a projected species richness map to assess changes in species occurrences, calculating the percentage of distribution loss or gain. This method considers the effects of climate change, natural cover loss, and varying FC implementation on species distribution.

We considered three future climate scenarios (SSP126, SSP245, and SSP585) and combined these with two land-use models based on the Forest Code—one representing the baseline (partial implementation) and the other representing full implementation. resulting in three emission-only scenarios and six combined (climate + land use) scenarios (Table 1).

To evaluate whether there were significant differences in species distribution loss under different climate change and land uses scenarios, we performed a two-way Analysis of Variance (ANOVA). This statistical test was chosen to investigate the main effects of the factors - climate and land use - along with their potential interaction. The model was fitted using the lm function in R (distribution loss ~ climate scenarios + land use), and the statistical significance of the effects was tested using the anova function from R stats package (R Core Team, 2021). After we conducted post hoc comparisons to identify which factor levels differ from each other, taking multiple comparison corrections into account, using the emmeans function (from the emmeans package) (Lenth, 2024).

Results

Species distribution models had a mean Sorensen performance of 0.75 ± 0.15, AUC of 0.80 ± 0.15, and TSS of 0.65 ± 0.19 (Figure S2).

When considering climate change alone, under the SSP126 scenario, species are predicted to experience an average distribution loss of 33 ± 28%, by 2050. This distribution reductions are expected to increase to 37 ± 30% and 41 ± 33% in the SSP245 and SSP585 scenarios, respectively (Figure S3).

Under all the climate change scenarios, most species will remain concentrated in the southern, southeastern, and central regions of the Brazilian Cerrado by 2050 (Figure S4). These regions, which currently have the highest species richness, are also expected to experience the greatest reductions in species richness (Fig. 1).

When considering climate and natural cover loss, nearly all species are expected to experience a reduction in their distribution to some extent, even under the most optimistic combination of scenarios analyzed (IFC-SSP126). Only three species, are projected to maintain their distribution. Up to eight species may potentially become extinct by 2050 under the BS-SSP585 (Fig. 2), and three within the BS-SSP126 scenario. Under the BS-SSP126, species are projected to lose an average of 59 ± 21% of their distribution by 2050. Distribution losses tend to increase to 61 ± 22% and 64 ± 23% in the BS-SSP245 and BS-SSP585 scenarios, respectively (Fig. 2).

The IFC slightly decreases the species loss by 2050 when compared to the BS scenario. In the BS-SSP126, species will lose on average 55 ± 22% of their distribution, increasing to 57 ± 23% and 60 ± 24% in the BS-SSP245 and BS-SSP585 scenarios, respectively (Fig. 2). Furthermore, it is important to note that all land-use scenarios could increase species distribution loss. However, IFC could reduce species distribution loss compared to the BS, in different greenhouse gas emission scenarios (Fig. 3; Table S6).

The ANOVA indicated significant main effects of both factors (ANOVA: *F*<sub>2,2173 < /sub> = 10.57, $p < 0.001$ for *climate*; *F*<sub>2,2173 < /sub> = 192.14, $p < 0.001$ for *land use scenarios*), with no significant interaction between them. Pairwise comparisons revealed statistically significant differences ($p < 0.05$) among OCC, IFC, and BS, following the pattern OCC < IFC < BS (Table S. This indicates that the IFC scenario significantly reduces species' distribution loss compared to BS scenario.

Considering the combined effects of climate and natural cover loss, the richness of Cerrado's endemic and endangered species will be mainly reduced in the southeastern and central regions of the Cerrado biome regardless of the scenarios (Fig. 4). This indicates that the regions with the highest current species richness, i.e., southern, southeastern, and central regions, will have the greatest net reductions in species richness under these scenarios. The SSP585 estimated a larger distribution loss than SSP45 in both the BS and IFC scenario; however, species loss is slightly reduced with FC implementation when compared to the BS (Fig. 4, Figure S5).

Discussion

We assessed how climate change and natural cover loss affect the distribution of endemic and threatened plants in the Brazilian Cerrado, emphasizing the role of the Forest Code in protecting and restoring native vegetation in this biome. Our results indicate that these factors will significantly reduce the geographic distribution of many species by

Table 1
The scenarios used were divided into two groups: emission-only (climate) scenarios and combined (climate and land use) scenarios. The emission-only scenarios include three climate pathways (SSP126, SSP245, and SSP585), which represent low, intermediate, and high emission futures, respectively. In the combined scenarios, each climate pathway is paired with two land-use models based on the implementation of the Brazilian Forest Code: the Baseline model (partial implementation) and the IFC model (full implementation).

Scenario Code	Scenario Type	Land Use Model	Climate Scenario	Description
SSP126	Climate-Only	–	SSP126	Low-emission future scenario.
SSP245	Climate-Only	–	SSP245	Intermediate-emission future scenario.
SSP585	Climate-Only	–	SSP585	High-emission future scenario.
BS-SSP126	Combined Climate + Land Use	Baseline (Partial FC Implementation)	SSP126	Low-emission future with partial implementation of the Forest Code.
BS-SSP245	Combined Climate + Land Use	Baseline (Partial FC Implementation)	SSP245	Intermediate-emission future with partial implementation of the Forest Code.
BS-SSP585	Combined Climate + Land Use	Baseline (Partial FC Implementation)	SSP585	High-emission future with partial implementation of the Forest Code.
IFC-SSP126	Combined Climate + Land Use	Full FC Implementation	SSP126	Low-emission future with full implementation of the Forest Code.
IFC-SSP245	Combined Climate + Land Use	Full FC Implementation	SSP245	Intermediate-emission future with full implementation of the Forest Code.
IFC-SSP585	Combined Climate + Land Use	Full FC Implementation	SSP585	High-emission future with full implementation of the Forest Code.

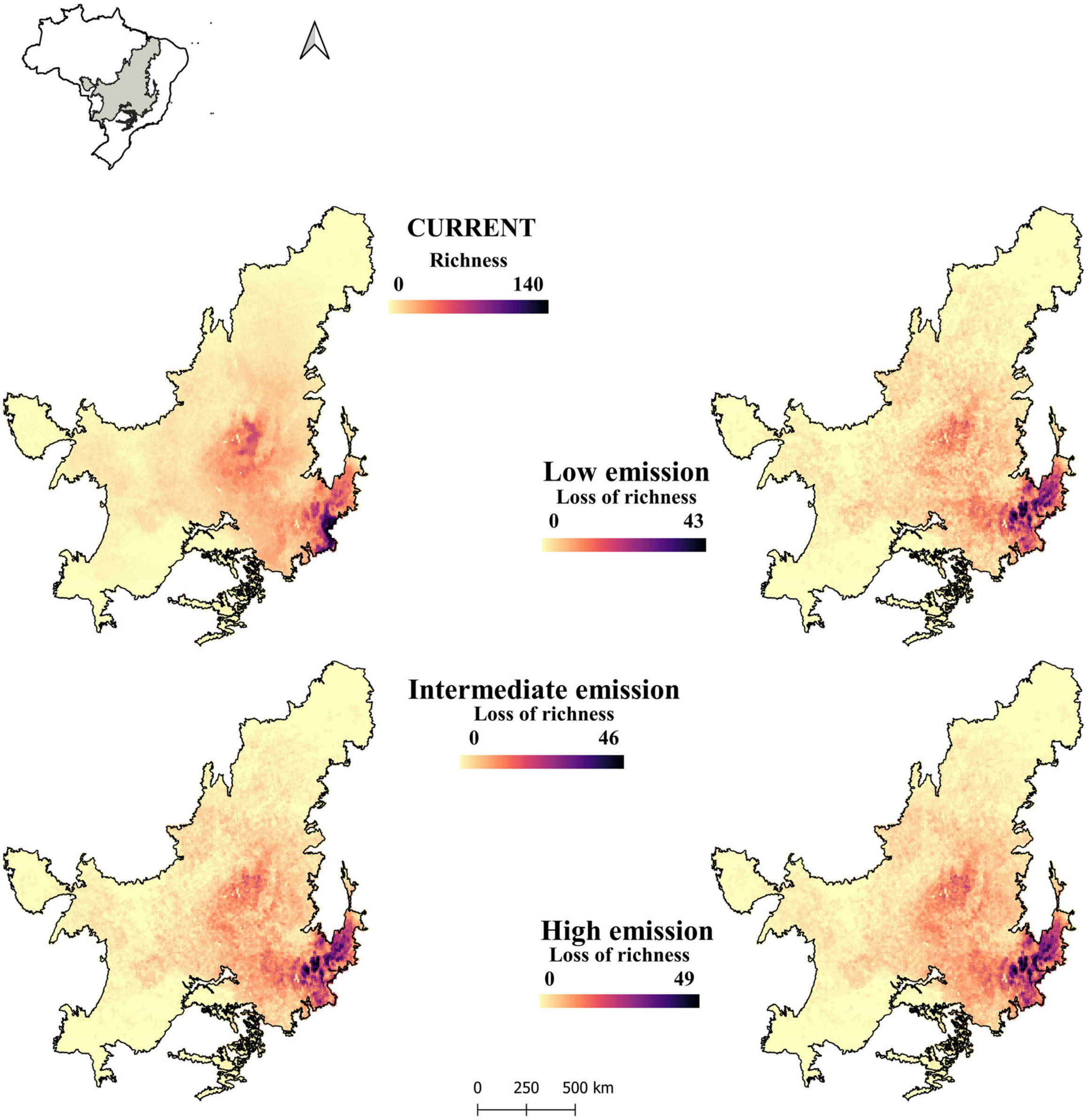

Fig. 1. Current richness of Cerrado endemic and endangered species, and projected species richness loss under future emission scenarios: Low emission (SSP126), Intermediate emission (SSP245) and High emission (SSP585). The maximum number of species lost per cell is indicated for each scenario.

2050, especially in areas with high species richness. Losses are expected even under optimistic scenarios and will be more severe without effective Forest Code implementation, highlighting the critical need for its full enforcement.

Threatened and endemic species of the Brazilian Cerrado will become more vulnerable to extinction in response to climate change, and the potential consequences of this should not be neglected at the ecosystem level. It is worth noting that while we have focused on the changes in species distribution, climate change can also affect species in various other aspects, including the reduction of suitability leading to mortality and extinction, altered recruitment dynamics, and disruption of biotic and abiotic interactions (Cahill et al., 2013; Simler-Williamson et al., 2019).

The origins and historical assembly of the Cerrado have been highly idiosyncratic, shaped by unique regional and continental geohistorical features and distinct evolutionary processes (Simon et al., 2009). The endemic flora of the Cerrado is characterized by a range of fire adaptations, which are hallmarks of many plant lineages in the biome (Gottsberger and Silberbauer-Gottsberger, 2006). These adaptations are strongly linked to fire resilience, a key factor for maintaining ecosystem stability and supporting natural regeneration in the Cerrado (Simon and Pennington, 2012). Additionally, endemic threatened species often fulfill specialized roles that are essential for ecosystem services (Durigan et al., 2022), including carbon sequestration, soil stabilization, and water regulation. Consequently, the potential loss of these endemic and endangered plant species could trigger cascading ecological effects, compromising the resilience of Cerrado ecosystems and hindering biodiversity conservation efforts.

Land-use change scenarios further increased species distribution loss. In recent years, Cerrado has experienced an increase in deforestation, greater than the other Brazilian biomes (Souza et al., 2020). Such deforestation pressure is primarily driven by agricultural expansion, as Brazil is an important global food supplier, and the Cerrado has been associated with large government projects of agricultural modernization (Da Silva et al., 2019). Although Brazil's Forest Code has low levels of protection in the Cerrado (20–35%) compared to the Amazon (80%), all IFC scenarios indicate a reduction in species losses relative to the BS scenarios.

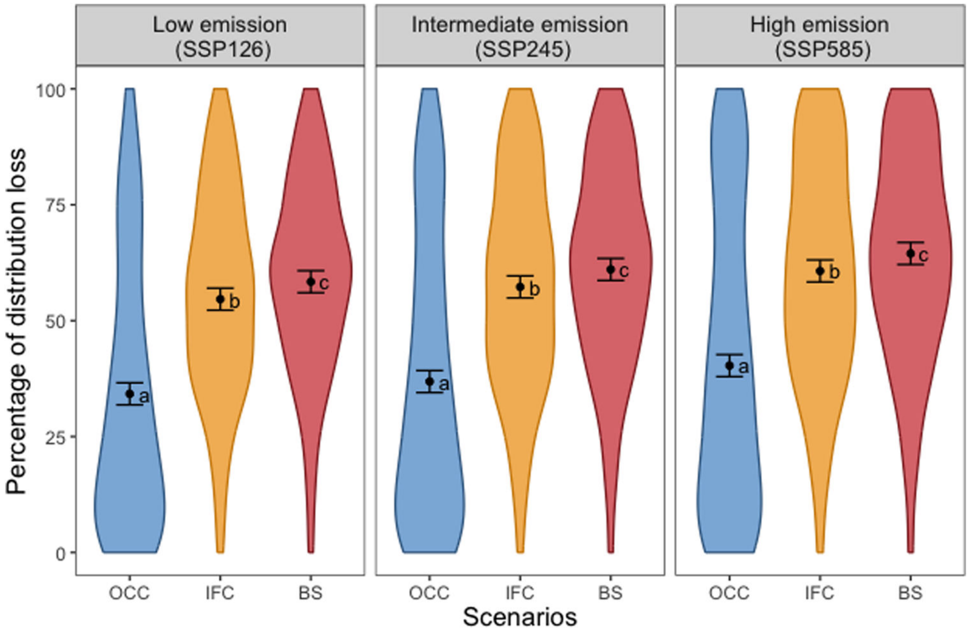

Fig. 2. The percentage of distribution loss under future climate change scenarios only (OCC) and associated with partial Forest Code implementation (BS) or full Forest Code implementation (IFC) scenarios. Black lines represent the mean distribution losses. The categories range from species that have not lost distribution (0%) to species that have become extinct (100%).

Our results also indicate that the southern and southeastern regions of the Cerrado host a large number of species under both current and future conditions, consistent with previous studies on Cerrado flora (Velazco et al., 2019, 2023) and fauna (Diniz-Filho et al., 2009). Although these areas can be considered refugia for the species, it is essential to highlight that these regions have experienced a significant loss of natural vegetation and extensive fragmentation (Strassburg et al., 2017). Consequently, the current land use conditions in these areas may jeopardize the long-term persistence of species (Loyola et al., 2012). In addition, rare and vulnerable species conservation should be based on the stability of habitats where these species currently inhabit (Geng et al., 2012), as even with the restoration of areas, as accounted for in the IFC land-use scenario, many species may not be able to recolonize these areas as quickly as needed (Brock et al., 2021).

An important instrument of Brazilian FC is the obligation to restore illegally deforested areas. Increasing natural vegetation cover, even in small fragments, can enhance connectivity and promote species persistence, increasing the ability to colonize new areas with suitable climatic conditions and enabling adaptive response to climate change in human-modified landscapes (Manning et al., 2009). However, although the IFC scenario considers restoration and we consider the recolonization of restored areas in our results, it is important to recognize that this recolonization may not always occur. The successful recolonization of degraded areas faces challenges at a landscape scale as dispersal limitations can prevent species from reaching restored habitats; Standish et al., 2007). Also, while richness recovery may occur, functional diversity may not be fully recovered as expected (Tölgyesi et al., 2019).

The land-use projections and scenarios from the GLOBIOM-Brazil model (Soterroni et al., 2019; Ramos et al., 2023) demonstrate the effect of implementing or not the major provisions of the FC, particularly deforestation control and large-scale native vegetation restoration. Although all land-use change scenarios led to increased loss in species distribution, the full implementation of the FC (IFC scenario) can reduce such loss.

Our results demonstrate that although the Forest Code (IFC scenario) may not prevent species extinctions under future climate and land-use change scenarios, it has the potential to reduce the severity of distributional losses for many species. For example, in SSP126, species losing 50–75% of their distribution decreased from 109 under the BS scenario to 91 with Forest Code implementation, while those losing 75–100% dropped from 59 to 49. Similar reductions were observed under SSP245, where species in the 50–75% loss category decreased from 104 to 87.

The observed reduction in distribution loss is a key positive outcome reflecting the role of habitat conservation and restoration under the Forest Code in mitigating the severity of distributional losses. While it may not prevent immediate extinctions, reducing the extent of distributional decline can increase the resilience of species and reduce their long-term extinction risk. This shift highlights the importance of full Forest Code implementation as a mitigation strategy. By limiting habitat loss and fragmentation, the Forest Code can buffer the impacts of climate change and land-use dynamics on species distribution, particularly in the Cerrado's southeastern and central regions, which harbor high biodiversity and are projected to experience significant losses.

Full compliance with the FC offers protection to biodiversity, emphasizing the importance of developing a policy mix that creates incentives for sustainable land use practices. It is important to highlight that the implementation of the FC alone is not enough to protect the Cerrado's biodiversity, given its low levels of protection within the biome. Thus, relying solely on the FC implementation will not be effective or sufficient under high-conservation strategies for the Cerrado. The Brazilian FC regulates deforestation on private lands; however, the areas considered legal for deforestation are much higher than those that would have to be restored to overcome illegal deforestation (Brancalion et al., 2016). Effective preservation of the Cerrado biome requires complementing FC implementation with additional conservation strategies such as expanding protected areas, establishing ecological corridors, payment for ecosystem services and undertaking restoration projects on both private and public lands (Pereira and Cestaro, 2016).

Models and scenarios are essential to guide the development and implementation of public policies, including land use policies, although their inherent limitations and uncertainties. Integrating climate and natural cover loss is particularly valuable, as it helps identify areas that may be favorable or unfavorable for species in the future under different scenarios. Considering climate and land use, decision-makers can make better choices when designing conservation strategies, habitat

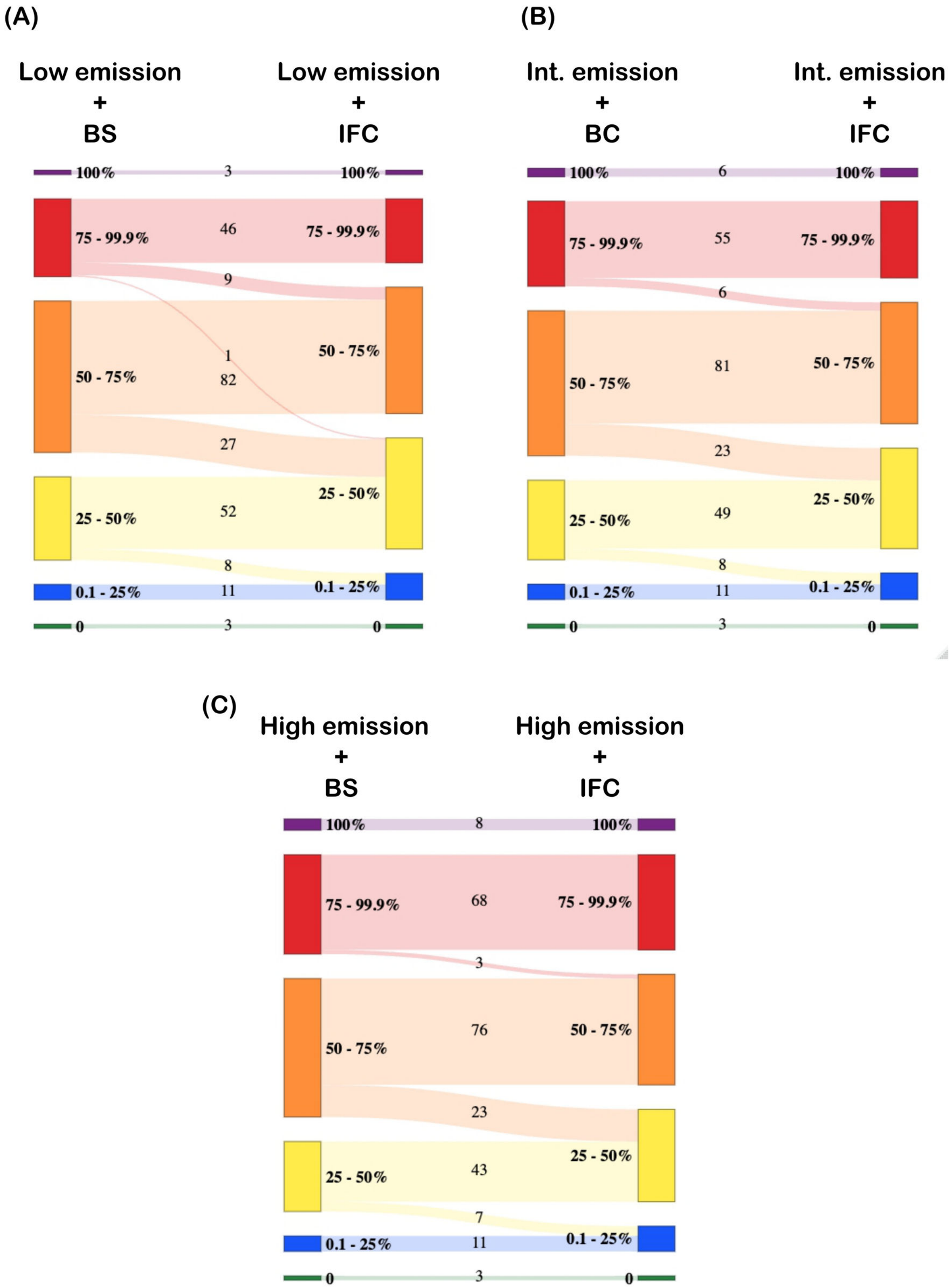

Fig. 3. Comparison of the number of species in each category of distribution loss between the partial Forest Code implementation (BS) and full forest code implementation (IFC) in 2050, under (A) low emission (SSP126), (B) intermediate emission (SSP245), and (C) high emission (SSP585) climate change scenarios.

protection, and restoration efforts. These findings provide important insights into the potential consequences of different land use policies and highlight the need to prioritize the effective implementation of the FC to mitigate species natural cover loss and advance biodiversity conservation in the Cerrado region.

CRediT authorship contribution statement

E.L.M.N. - Conceptualization; Data curation; Formal analysis; Writing - original draft and review & editing. **G.T.** - Conceptualization; Data curation; Formal analysis; Writing original draft and review & editing, Project administration. **S.J.E.V.** - Methodology; Formal analysis; Writing original draft and review & editing. **F.M.R.** - Data curation;

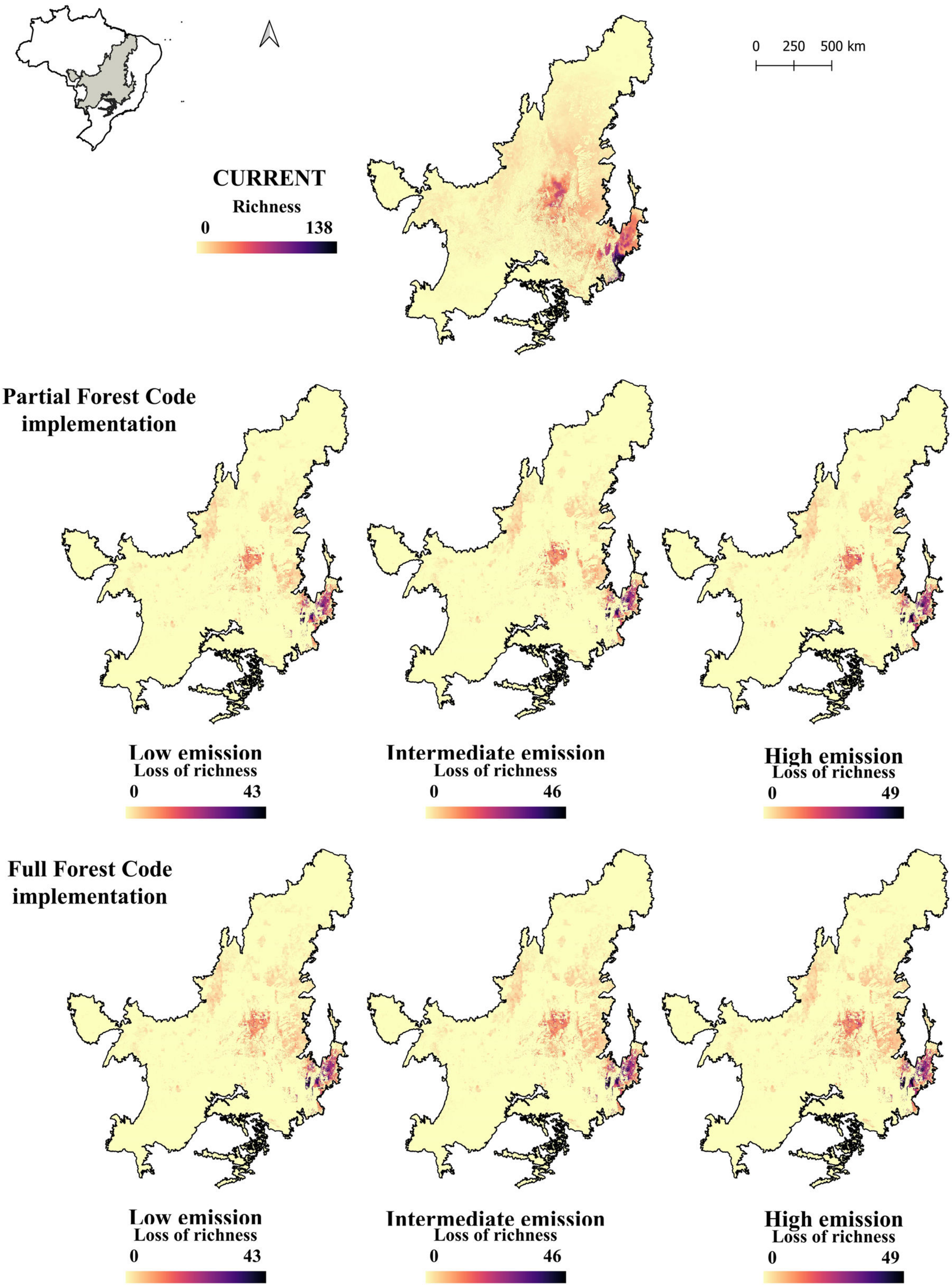

Fig. 4. Current richness of Cerrado endemic and endangered species, and projected richness loss under future emission scenarios and associated with land use change scenarios related to the implementation of FC (2050).

Methodology; Validation; Writing - review & editing. **R.G.R.** - Data curation; Methodology; Validation; Writing - review & editing. **A.C.S.** - Data curation; Methodology; Validation; Writing - review & editing.

Declaration of competing interest

All authors of this manuscript declare that they have no conflicts of interest that could inappropriately influence or bias the content of this research. We have no financial, personal, or professional affiliations or relationships that could be perceived as conflicts of interest in the context of this work.

Acknowledgements

ELMN was supported by CAPES Master's scholarship. GT was supported by PNPD/CAPES postdoc fellowship number PNPD20132984-52012018005P7. SJEV thanks the Center for Open Geographical Science (COGS), Department of Geography, at San Diego State University for the research support. We also thank to Paulo De Marco Jr. and André Andrade for insightful comments in previous versions of this manuscript.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.pecon.2025.08.007.

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