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A dark scenario for Cerrado plant species: Effects of future climate, land use and protected areas ineffectiveness

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Abstract

Aim: The anthropogenic climate change and land use change are considered two of the main factors that are altering biodiversity at the global scale. An evaluation that combined both factors can be relevant to detect which species could be the most vulnerable and reveal the regions of highest stability or susceptibility to biodiversity. We aimed to: (a) assess the effect of climate change and land use on the distribution of Cerrado plant species for different countries where they occur, (b) evaluate the effectiveness of the current network of protected areas (PAs) to safeguards species under different greenhouse–gas (GHG) emissions and land use scenarios, and (c) estimate the vulnerability of species based on protection effectiveness and habitat loss.

Location: Bolivia, Brazil and Paraguay.

Methods: We modelled the distribution of 1,553 plant species of Cerrado and evaluated species range loss caused by present and future land use and two GHG for 2050 and 2080. We assessed species vulnerability combining the representativeness of species within conservation units with the loss of species' ranges outside PAs.

Results: We found that climate change and land use will cause great damage to Cerrado flora by 2050 and 2080, even under optimistic conditions. The greatest impacts of land use will occur in the regions where the greatest richness will be harboured. The conservation of the species will be seriously affected since the PA network is not as effective in safeguarding them under current or future conditions.

Main conclusions: The low level of protection together with the losses caused by the advance of agricultural lands will lead most species being highly vulnerable. Due to the distinct impacts of climate and land use over the three countries, conservation strategies should be implemented at transboundary and national levels.

KEYWORDS

neotropical savannas, protected areas network, species distribution models, vulnerability

1 | INTRODUCTION

Despite Earth has experienced several natural climatic fluctuations throughout geological time, the rate of contemporary climate change has boosted due to the impacts of human activities (Diffenbaugh & Field, 2013). Greenhouse–gas (GHG) emissions are the highest in history, putting ecosystems, societies and the economic sectors at risk (IPCC, 2014). Such anthropogenic climate change is considered one of the main factors altering community composition and ecosystem functioning at the global scale (Pecl et al., 2017). However, despite its pervasive impacts, climate change is not the sole responsible for biodiversity decline. Habitat loss due to anthropic land use is an important factor that drives current biodiversity to a worldwide crisis (Newbold et al., 2016). The increase of human demand for food and energy has led to the conversion of large areas of natural cover into production lands (Alexandratos & Bruinsma, 2012) and, consequently, most of the world's land area is now ecologically compromised (Foley et al., 2005; Newbold et al., 2016). The effects of both climate change and loss of natural cover compromise not only biological diversity but also human well-being (Hautier et al., 2015; Pecl et al., 2017). Hence, a new climate and the expansion of production lands already challenge biodiversity conservation worldwide.

From an anthropocentric viewpoint, there is no doubt about all the benefits that biodiversity brings to human beings and, therefore, the importance of conserving it (Pearson, 2016). Nonetheless, conservation actions may be compromised or limited by economic interests (Margules & Pressey, 2000), which may represent conflicts between conservation and development (Balmford et al., 2001). In order to halt the loss of biodiversity, international conservation targets and agreements have been established, such as the United Nation's Sustainable Development Goals (United Nations General, 2015) and the Convention on Biological Diversity (https://www.cbd.int/sp/targets/#GoalA). Nevertheless, for achieving such international goals it is imperative to guarantee an appropriate management of protected areas (PAs) and strategic expansion (Le Saout et al., 2013). However, the factors that determine PAs allocation are not necessarily based on ecological criteria, for instance being commonly biased to country borders or isolated areas (Baldi, Texeira, Martin, Grau, & Jobbágy, 2017; Margules & Pressey, 2000), which can compromise the effectiveness of species protection (Gray et al., 2016). In addition, the demand of space for future land uses could jeopardize the expansion of PAs (Pouzols et al., 2014).

The PAs are conceived to protect biodiversity and, consequently, to safeguard a proportion of species geographical distribution from disturbances (Rodrigues et al., 2004; Thomas et al., 2012). Nevertheless, the remaining unprotected distribution of species may be altered by both loss of natural cover and climate change. land use changes shape important landscape characteristics such as the degree of connectivity, fragmentation and edge effects, affecting the persistence species' populations (Fahrig, 2001; Swift & Hannon, 2010). In addition, such landscape disturbances may interact with climate change, having a negative synergistic effect on diversity (Oliver & Morecroft, 2014). However, considering that the geographical distribution of species may be altered due to climate change, existing PAs may become ineffective in conserving biodiversity (Monzón, Moyer-Horner, & Palamar, 2011). The degree of representativeness of a species range within PAs (hereafter called protection degree) and its remaining range outside PAs gives a notion of a species' vulnerability to extinction (Figure 1). For instance, a species may have a lower vulnerability even when having its range totally unprotected, because its distribution is mostly within zones not affected by anthropic land use. The most common scenario, however, is that a higher proportion of species' ranges within PAs represents the less vulnerable component of species' distributions. The worst scenario occurs when a species loses territory within PAs caused by climate change while also loses range outside PAs due to land use expansion and/or contraction of species distribution by climate (Figure 1).

Despite harbouring ecoregions with high biodiversity and endemism (e.g., Tropical Andes, Atlantic forest or Cerrado), South America has faced intense habitat loss, resulting in fragmented and anthropized ecosystems (Fehlenberg et al., 2017; le Polain de Waroux, Garrett, Heilmayr, & Lambin, 2016; Overbeck et al., 2015; Strassburg et al., 2017; Tejada et al., 2016). A clear example of this situation is the Cerrado ecoregion. Outstanding by its high diversity and degree of endemism, the Cerrado is among the most diverse Neotropical savannas (Silva & Bates, 2002). Essentially located on the Central Plateau in Brazil represents the second largest Brazilian ecoregion (Ratter, Ribeiro, & Bridgewater, 1997). Cerrado also expands to two neighbouring nations, Bolivia and Paraguay, being present in the Dry Chaco, Chiquitano Dry Forest, Beni Savanna and Pantanal ecoregions (Beck, 2015; Ibisch, Beck, Gerkmann, & Carretero, 2003; Mereles, 2013; Villarroel, Munhoz, & Proença, 2016). In Brazil, the advance of agribusiness over large areas has

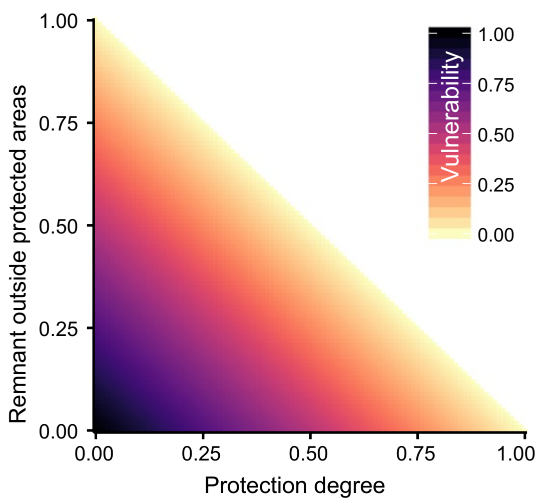


FIGURE 1 Vulnerability degree based on the relationship between the species protection degree (i.e., species geographical distribution within protected areas) and the relative area outside PAs (i.e., the remaining unprotected part of the species geographical distribution). It is assumed a scenario in which PAs are affected by the drift of species distribution because of climate change, while outside PAs the range of species is affected by climate change and land use

caused the rapid disappearance of ecosystems and habitats characteristic of Cerrado, leaving it as a highly threatened and fragmented ecoregion with <20% of its remaining area undisturbed (Strassburg et al., 2017). Furthermore, this ecoregion is poorly protected, with only 7.7% of its surface under protection (Oliveira et al., 2017). Unfortunately, in the other two countries that can preserve part of the Cerrado flora, Bolivia and Paraguay, are also vulnerable given the rapid change of their natural cover (Redo, Aide, & Clark, 2012; Salazar, Baldi, Hirota, Syktus, & McAlpine, 2015; Salazar et al., 2015; Vallejos et al., 2015).

The proper management and conservation of biodiversity should take into account the impact of climate change and trends in land use (Pecl et al., 2017; Pouzols et al., 2014). Thus, explicitly considering future threats and species sensitivity to such factors is crucial for the establishment of more effective conservation actions (Payne & Bro-Jørgensen, 2016). An evaluation combining both land use and the potential effects of future climate conditions can be relevant to detect which are the most vulnerable species, as well as reveal regions of highest stability or susceptibility to biodiversity loss. Such assessment is necessary to be performed at global and regional scales because countries present different patterns of exploitation of their resources (Armenteras, Espelta, Rodríguez, & Retana, 2017) and share many species (Hunter & Hutchinson, 1994). In this sense, here we (a) determine the effect of climate and land use change on the distribution of Cerrado's plant species across the different countries where this ecoregion occurs (Bolivia, Brazil and Paraguay), (b) evaluate the effectiveness of the current PA network to safeguard species under different GHG emissions and land use scenarios, and (c) estimate the vulnerability of species taking into account both representativeness within PAs and the effects of habitat loss outside PAs.

2 | METHOD

2.1 | Study area

The study area includes the countries of Bolivia, Brazil and Paraguay where the Cerrado is present. Although Cerrado's boundaries are well defined in Brazil, there are disagreements about its limits in Bolivia and Paraguay. Therefore, we used the WWF's Terrestrial Ecoregions of the World (Olson et al., 2001) to overcome the methodological differences used to define ecoregions within each nation. We included ecoregions related to open formations such as steppes and savannas, and others that are not open formations but well known for the existence of Cerrado within them (Ribeiro & Walter, 2008). Therefore, the study area comprised the ecoregions of Cerrado, Beni Savanna, Campos Rupestres Montane Savanna, Chiquitano Dry Forest, Dry Chaco, Humid Chaco, Maranhão Babaçu Forests and Pantanal.

2.2 | Species records and data cleaning

We modelled trees, shrubs, subshrubs, vines and herbs that inhabit the Cerrado vegetation domain of Bolivia, Brazil, and Paraguay. Because of high plants diversity, it is difficult to determine which taxa are well distributed within the Cerrado ecoregion or occur in a marginal way, given that several species are predominant in other neighbouring ecoregions (Françoso, Haidar, & Machado, 2016). For this reason, we created a plant species list of the Cerrado for the three countries and then selected the taxa based on different criteria (see Supporting Information Appendix S1 about Cerrado species list and species selection).

To appraise species distribution, we used the species records at GBIF (www.gbif.org/); speciesLink (http://splink.cria.org.br/); ICMBio (https://biodiversidade.icmbio.gov.br/); Plant of Bolivia (http://herbaria.plants.ox.ac.uk/bol/boliviajriwood); and Tropicos. We checked, corrected and updated the species names of every record using the TNRS v4.0 (Boyle et al., 2013) for the species without information in this webpage were checked using The Plant List 1.1 (http://www.theplantlist.org/) and Tropicos (see Supporting Information Appendix S2 for occurrence cleaning procedure).

We added occurrences georeferenced at the municipal level provided by the speciesLink for those species with fewer than 20 cleaned occurrences. We only considered those records located in municipalities with a variation coefficient of current environmental conditions ≤15% for any of the 11 variables used for constructing the models (for further information about the selection of municipal georeferenced records see Supporting Information Figure S1). Species occurrence records are commonly biased throughout space, and several approaches exist to correct this bias in the geographical or environmental space (Fourcade, Engler, Rödder, & Secondi, 2014; Varela, Anderson, García-Valdés, & Fernández-González, 2014). We used a systematic sampling approach to correct species occurrence bias because it is a simple procedure with good performance (Fourcade et al., 2014). To do so, we filtered species occurrences by randomly sampling one occurrence within each grid cell of a grid with a grain twice the resolution of the environmental variables. Only species with more than five records (after cleaning) were modelled. Thus, the final database comprised 132,450 records for 1,553 species.

2.3 | Environmental data

The environmental variables used to construct the niche models (ENMs) considered both edaphic and climatic factors because the use of both may improve the performance of ENMs (Velazco, Galvão, Villalobos, & Marco, 2017). We used six soil variables related to physical soil properties provided by the SoilGrids (Hengl et al., 2017) with 0.75 arc-seconds resolution (c. 250 m), which were upscaled to 5 arc-min (c. 10 km) by taking the average value of higher resolution cells into lower resolution cells. We used 19 bioclimatic variables as climatic predictors for current and future conditions. Current climatic conditions were obtained from WorldClim 2.0 (Fick & Hijmans, 2017) with 5 arc-min resolution. Climatic and edaphic databases summed up to 25 variables and 49 raster layers (see the complete list of variables in Supporting Information Table S1). We performed a principal component analysis (PCA) on the current environmental variables based on a correlation matrix, to overcome multicollinearity problems and reduce the number of predictors variables. We selected nine principal components (PCs) which explained up to 95.20% of the total variance from the original environmental variables (see Supporting Information Table S2 and Figure S2). We used the PCA's eigenvectors to calculate scores of each derived PC which were used as new predictors. These same eigenvectors were used calculate scores for future times based on environmental variables for future conditions (see below).

We used the climate projection from the 5th assessment report of the Intergovernmental Panel on Climate Change as the source of future climate conditions. We evaluated the effect of climate change using two Representative Concentration Pathways (RCP). They were the medium stabilizing 4.5 W/m^2 and very heavy 8.5 W/m^2 radiative forcing levels (van Vuuren et al., 2011), hereafter RCP4.5 and RCP8.5, respectively. These RCPs were assumed as optimistic and pessimistic scenarios, respectively. We used projections for 2050 (mean for the period from 2041 to 2060) and 2080 (mean for the period from 2071 to 2090).

Uncertainty on the estimation of future species ranges may be due to the use of different ENM algorithms and Atmosphere-Ocean Global Circulation Models—AOGCMs—(Watling et al., 2015). As many AOGCMs are available for the region and in order to avoid their subjective selection, we use an adaptation of the Casajus et al. (2016) approach. This procedure was performed for both RCPs (4.5 and 8.5) by the year 2050 based on 28 AOGCMs from the Global Climate Model database (http://ccafs-climate.org/; see Supporting Information Appendix S3, Table S3 and Figure S3 for further information about AOGCMs selection). Thus, we used seven AOGCMs: CESM1-BGC, CSIRO-ACCESS-1.3, FIO-ESM, GFDL-ESM2G, GISS-E2-R, IPSL-CM5A-LR and MOHC-HADGEM2-ES.

2.4 | Land use data

In order to evaluate the effect of land use trends, we used current and future land cover provided by the land use Harmonization (http://luh.umd.edu/code.shtml) estimated by 2015, 2050 and 2080 (Hurtt et al., 2011). The models MESSAGE-GLOBIOM and EMIND-MAGPIE were selected because they are consistent with the GHG emissions scenarios RCP4.5 and RCP8.5, respectively. As these data are available with a resolution of 0.25 degrees, we downscaled them by the bilinear method to 5 arc-min to have the same resolution of the environmental variables (Newbold, 2018). We quantified habitat loss by using the land use classes: C3 and C4 annual crops, C3 and C4 perennial crops, C3 nitrogen-fixing crops, urban, managed pastures and rangelands. All crop categories were grouped under the category of croplands. Managed pastures and rangelands do not imply a total loss of natural cover but, given that they are anthropized, can harbour conditions that promote or demise the presence of a species, or even some species can adapt to the absence of natural habitat (Karp et al., 2012; Mendes & De Marco, 2017). Here, we considered that these land uses exert a negative impact on species in general.

2.5 | Modelling procedures

Several correlative methods have been proposed for constructing ENMs, which may show variable performance depending on the condition of the modelling and its objective (Zhu & Peterson, 2017). For this reason, ensemble models based on several algorithms are advisable (Araújo & New, 2007). We used six ENM algorithms: Generalized Linear Models, Generalized Additive Models, Maximum Entropy, Random Forest, Support Vector Machine and Gaussian Processes (see Supporting Information Appendix S4 for further information about how different ENMs were fitted). The area used to adjust ENMs predictions must encompass the regions accessible to the species over relevant periods of time (i.e., M component of the BAM diagram; Soberón & Peterson, 2005). Such area affects ENMs projections and model accuracy (Acevedo, Jiménez-Valverde, Lobo, & Real, 2017; Barve et al., 2011; Saupe et al., 2012). Given the difficulty to define these areas for a large set of species that do not have fossil data or estimates of dispersal capacity, we defined them based on the ecoregions where the occurrence records of each species are located, thus assuming that these areas were accessible to the species (Barve et al., 2011; Soberón, 2010). The ecoregion boundaries were sourced by WWF's Terrestrial Ecoregions of the World (Olson et al., 2001).

2.6 | Model evaluation, ensemble forecast and overprediction correction

We used two approaches to evaluate ENM performance. For species with 5–15 occurrence records, we used the jackknife procedure, where each partial model is constructed with n – 1 records. For species with ≥16 occurrence records, we implemented a block fold-validation (Roberts et al., 2017) with two partitions (like a checkerboard) in order to control for spatial autocorrelation between training and testing data (Supporting Information Appendix S5). We used the True Skill Statistic (TSS) as a metric of model performance (Allouche, Tsoar, & Kadmon, 2006).

We applied two-instance ensemble forecast procedure, an ensemble for ENM algorithms and the other for the AOGCMs predictions. For the algorithm ensemble, we used the arithmetic average of the suitability predicted by the best algorithms of a species, that is, those models with a performance greater than or equal to the algorithms' average TSS. We built the final future projection by performing a new average of suitability values obtained with the seven AOGCMs data used in the models selected in the previous ensemble step. We used the threshold that maximizes the sum of the sensitivity and specificity to transform continuous models (current or forecasted) to a binary (presence–absence) model. This threshold was calculated based on the ensembled models under current conditions. Thus, we constructed 9,336 models (Species × Algorithms), with 261,408 projection (AOGCMs × RCPs × Periods) that constituted the 6,224 final models (Species × RCPs × Periods).

Commonly, when ENMs are projected throughout the study region, they predict climatically suitable areas that can be far from the observed species distribution (Peterson et al., 2011). To correct this overprediction, we only selected those suitable patches that met two criteria: (a) had at least one occurrence record, or (b) had no occurrences but were separated to those that did by less or equal than a certain distance *d*. The *d* was determined by the lower quartile of the pairwise distance between patches with and without presences. Selection of *d* by this method allows capturing the spatial structure of suitable patches and at the same time avoids using an arbitrary value.

2.7 | Protected areas network

We assembled the spatial information of different PAs categories for the three countries to construct the PA network of our study area. We used the indigenous lands as well as the municipal, departmental and national PAs from Bolivia sourced by the *Servicio Nacional de Areas Protegidas* updated to 2015 (http://geo.gob.bo), the public and private PAs from Paraguay sourced by the *Secretaría del Ambiente* updated to 2007. The integral protection areas, sustainable use areas and indigenous lands from Brazil, the first and second one sourced by the *Ministério do Meio Ambiente* updated to 2017, and the third one from *Fundação Nacional do Índio* updated to 2013, these data were sourced by *Laboratório de Processamento de Imagens e Geoprocessamento* (http://maps.lapig.iesa.ufg.br/lapig.html). We constructed a raster layer using this PA dataset by rasterizing it to the resolution of the environmental data (i.e., 5 arc-min). We considered as protected those grid cells that were overlapped by a PAs in a proportion ≥10%.

2.8 | Data analysis

We determined the effect of climate change on species distribution by considering a scenario of non-dispersal; that is, future distribution ranges are determined only by those areas where present and future suitable conditions overlap. We considered this as a convenient procedure given the evidence that a non-dispersal situation can occur in plants (Zhu, Woodall, & Clark, 2012). In addition, this choice may produce a conservative scenario for species protection, which is possibly a better choice for conservation planning in a situation of persistent gaps of knowledge about species traits.

We assessed the relative species' distributional loss for the whole study area and for each country caused by climate and climate plus land use. These were calculated by the ratio between the range lost by different factors (i.e., climate and climate plus land use) and the original distribution range (i.e., assuming a baseline landscape without anthropic land use). We also calculated the contribution that each land use category made to the distribution losses of the species.

The protection degree of species was calculated by the ratio between the species' distribution area within the PA network, either for current or future conditions, and the original distribution range for the current condition. The species' distribution losses within the PA network for future conditions were based on the ratio between lost range of the species within PAs in the future and the current range within PAs. Protection degree and loss within PAs were calculated for the whole study area and for each country.

We assessed the species vulnerability combining two factors (a) the degree of conservation of a species, considered here as the proportion of a species' distribution within conservation units, and (b) the loss of species range outside PAs (Figure 1). The vulnerability of a species, for present and future conditions, was calculated by the expression $V = 1 - (P + L)$, where V is the vulnerability level, P the protection degree of a species, and L the relative remnant distribution outside PA network. Species vulnerability is equal to 0 if $P + L = 1$; that is, the total species range is distributed in undisturbed areas, within PA network or both.

Data processing, construction of the ENMs and analyses were conducted in the R environment 3.4.1 (R Core Team, 2017; see Supporting Information Appendix S6 a complete list of R packages used).

3 | RESULTS

We modelled 1,553 plant species comprising trees (151), shrubs (450), subshrubs (275), vines (88) and herbs (589). Models showed a satisfactory performance with TSS for all species of 0.76 with a standard deviation of ±0.16 (see Supporting Information Figure S4). Under current conditions of land use, the distribution of species was less than half of their complete modelled distribution (i.e., assuming a scenario without anthropic disturbance). These losses are different among nations. Bolivia is the country where species were least impacted by current land use, while Paraguay suffered the greatest losses of its national flora (Figure 2a).

Our results showed that all species will have their distributions affected at some level for future climate conditions, even under the most optimistic scenarios. The RCP4.5 scenario predicts that species will lose an average of 34%–40% of their distribution between 2050 and 2080, respectively; and 15–21 species are likely to become extinct (i.e., with no suitable cells). Distribution losses tend to increase under RCP8.5 with an average range loss of 43%–60% and 25 and 51 species may become extinct within each time period, respectively. Paradoxically, species from Bolivia, which is the country with the lowest land use effects, will have the greatest losses due to climate change in both scenarios (Figure 2b).

We predicted a considerable increase in distributional losses when the effects of climate and land use were combined for the whole study region. The RCP8.5 estimated higher distributional losses than RCP4.5, with 26 and 55 species potentially going extinct in by 2050 and 2080 (Figure 2c). The combined effects of climate and land use were different for the flora of each country. Although high, Bolivia will have the lowest effects of these changes. In Brazil, species' distributional losses were estimated to be proportionally similar to those of the whole region, whereas Paraguay will have the highest distributional losses (Figure 2c).

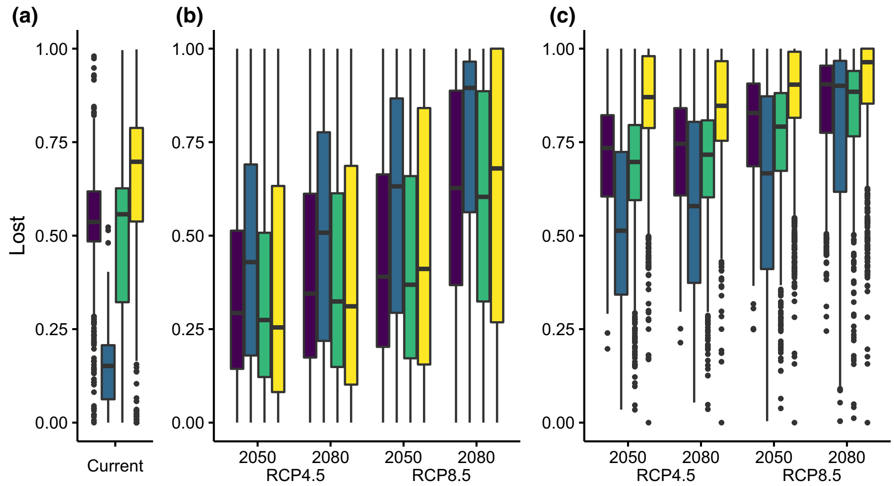


FIGURE 2 Boxplot with relative distributional loss of Cerrado's plant species by land use under current conditions (a), future climate (b) and future climate and land use (c) under optimistic (RCP4.5) and pessimistic (RCP8.5) GHG emissions scenarios forecasted for 2050 and 2080. Each colour depicts different extents of assessment; for the whole study area (violet), and the nations of Bolivia (blue), Brazil (green) and Paraguay (yellow). Species losses assumed no dispersal to new suitable environmental conditions. The proportion of losses were calculated based on the potential distribution of species on the baseline landscape assuming unused primary vegetation. Distributional losses for each country were computed based on the original distribution of species within each nation

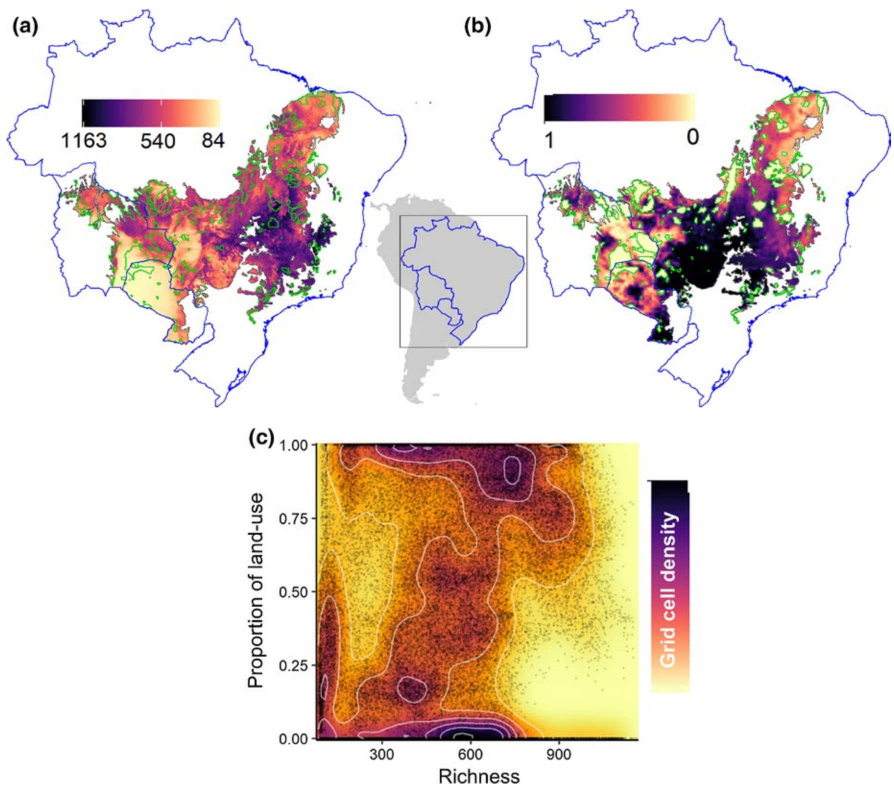


FIGURE 3 Current distribution of Cerrado plant species (a), proportion of grid cell occupied by anthropic of land use (b), and density plots depicting the relationship between richness and land use. Green polygons represent the current PA network. Darker colours on panel (b) represent areas with a larger proportion of a cell occupied by anthropic land use. Each point depicted in the panel (c) represents a grid cell of the study area where the darkest regions depict higher concentration of points

A total of 55 species can potentially go extinct due to climate change and land use expansion under some of the scenarios and forecasting date for the whole study area. Among these species, some are already threatened with extinction (following IUCN Red List criteria), 11 are endangered, five vulnerable and two near threatened (see Supporting Information Table S4).

For the current land use condition, the greatest species' distributional losses (compared with a non-disturbed habitat scenario) for the whole study area were caused by rangelands, followed by croplands. In Bolivia and Brazil, rangelands are the main loss factors; in Paraguay, this land use represented 50% of losses and managed pastures are the second largest factor. Under RCP4.5 and considering the entire region, the negative effects of rangelands are reduced with an increase of threat from croplands. A considerable increase in cropland impact is estimated for the entire region for the RCP8.5. This land use type is expected to be higher in Brazil than in the other countries (Supporting Information Figure S5).

The predicted richness pattern under current environmental conditions showed that the main concentration of species is in the central and central-east area of the Cerrado ecoregion in Brazil. In Bolivia, the highest plant richness is in the eastern area in the Chiquitano Dry Forest and Dry Chaco and eastern extreme of Humid Chaco in Paraguay (Figure 3a). More importantly, regions with the highest predicted plant richness are concentrated over extensively disturbed areas in central Brazil. This situation is less pronounced in Bolivia, as the most disturbed regions are in places with lower richness (Figure 3a,b).

Most of the cells of our study area will reduce their species richness for both GHG emissions scenarios mainly under the RCP8.5 (Figure 4a). For 2080, the region with the highest species richness will be in central-eastern and southern-eastern region of the Cerrado ecoregion in Brazil. In Bolivia, the richest area will be in the Cerrado ecoregion near the Brazilian border, with additional important areas located in the Chiquitano Dry Forest, Dry Chaco and Beni Savanna. In Paraguay, plant richness will concentrate in the eastern of Humid Chaco (Figure 4a,b). The areas with the most intense land use will be coincident with that area highlighted as the richest for both forecasted year and GHG emissions scenario (Figure 4b,c).

Regarding the patterns of species loss due to climate change, the greatest net losses for both GHG mission scenarios will occur mainly in the northern and north-western regions of Bolivia and in the central region of the Cerrado in Brazil (Supporting Information Figure S6). In the case of relative loss values (i.e., the ratio between the richness that will be lost in the future and the current richness), the highest values for the optimistic scenario are concentrated in the ecoregion of Beni and south-east Bolivia, as well as in the Pantanal (Supporting Information Figure S7).

Current conditions of the protection degree show that most species are poorly represented within the PA network because of c. 1,400 species have <25% of their distribution under protection. With respect to protection within each nation (i.e., the relationship between the range of species within national PAs and the area occupied by the species within that nation), species in Bolivia have the highest protection degree, followed by Brazil and Paraguay (Figure 5a).

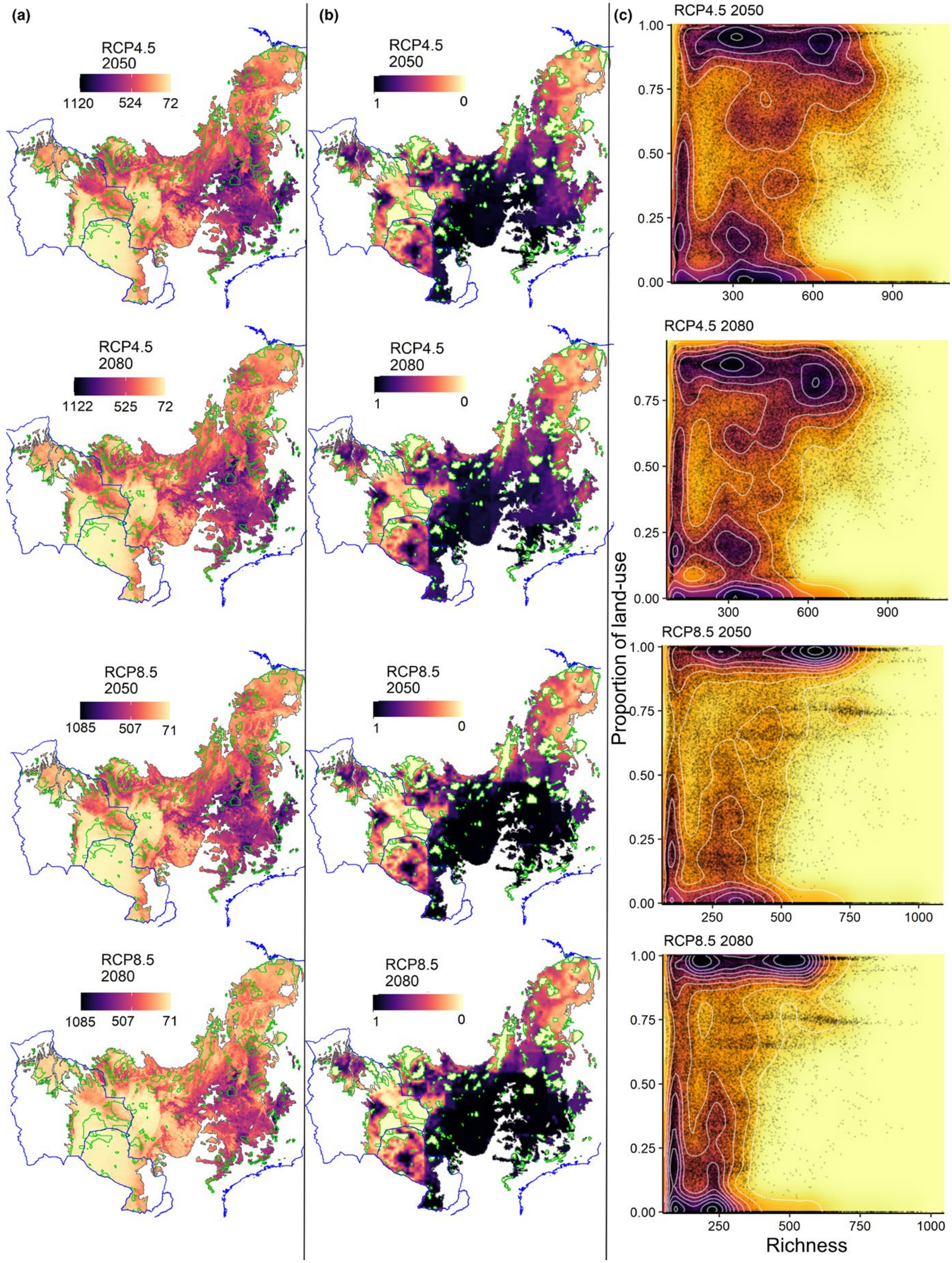
For the RCP4.5, species are expected to lose on average 30% and 36% of their current protected distribution by 2050 and 2080, respectively. Such losses will be higher for the RCP8.5 (Figure 5b). At the national level, it is estimated that all countries will have an increase in the distributional losses within PAs, with a maximum for the year 2080 and RCP8.5. In this way, Brazil will show the lowest values, but still high, as they increase to 50% by 2080. The situation in Bolivia and Paraguay will be more critical as average values by 2080 will be >75% (Figure 5b).

Regarding the vulnerability based on the relationship between the protection degree, and the remaining area outside the PA network (Figure 1); currently, most species have a vulnerability of 0.6 mainly due to low species protection degree followed by, the loss of their range outside the PA network (Figure 6a,b). Under the RCP8.5, an increase of lost area outside PA network by climate and land use will lead to an increase in the vulnerability of species by 2050, however, the species-area loss within the PA network will substantially contribute to the vulnerability of species by 2080 (Figure 6a,e,f). Of the total modelled species, 93 had a vulnerability value equal to or above the upper quartile for current condition and both RCP scenario and forecasted year. Of these species, 19 are currently under threat status, one as critically endangered, four vulnerable, four near threatened and ten as least concerned (see Supporting Information Table S5).

4 | DISCUSSION

In this study, we: (a) evaluated the effects of climate and land use changes on the distribution of Cerrado plant species for two GHG emission scenarios, (b) assessed the effectiveness of the PA network to maintain these taxa, and (c) measure their vulnerability under current and future conditions. We found that climate change and land use will greatly reduce the potential geographical distribution of species by 2050 and 2080. Loss of natural cover may compromise the areas that will be climatically suitable in the future, and thus, the most disturbed areas are coincident with the regions where both current and future species richness were predicted to be greatest. Such interaction between climate and land use could cause substantial species' distributional losses in each country, seriously compromising conservation efforts. Currently, the PA network is not effective in safeguarding Cerrado plant species due to the low representativity of the species within conservation units, nor it will be for future conditions due to the loss of suitable areas. At the national level, the three countries had distinct PA effectiveness. However,

FIGURE 4 Future richness distribution of Cerrado plant species (a), proportion of grid cell occupied by anthropic of land use (b), and density plots depicting the relationship between richness and land use (c) under optimistic (RCP4.5) and pessimistic (RCP8.5) GHG emissions scenarios forecasted for 2050 and 2080. Future richness projections are based solely on species stable areas assuming a scenario without dispersion. Green polygons represent the current PA network. Darker colours on panel (b) represent areas with a larger proportion of a cell occupied by anthropic land use. Each point depicted in the panel (c) represents a grid cell of the study area where the darkest regions depict higher concentration of points


(a)
RCP4.5
2050
1120 524 72
RCP4.5
2080
1122 525 72
RCP8.5
2050
1085 507 71
RCP8.5
2080
1085 507 71
(b)
RCP4.5
2050
1 0
RCP4.5
2080
1 0
RCP8.5
2050
1 0
RCP8.5
2080
1 0
(c)
RCP4.5 2050
RCP4.5 2080
RCP8.5 2050
RCP8.5 2080
Proportion of land-use
1.00
0.75
0.50
0.25
0.00
300 600 900
250 500 750 1000
Richness

the different projections predict that countries that are currently promising to conserve the Cerrado flora might not be effective for future conditions. This low protection degree and susceptibility to climate change, along with a more intensive and extensive land use would lead the species to be severely threatened, even under the most optimistic scenario.

The mechanisms by which climate change affects a species are complex and, in addition to species' geographical displacements, it affects species in a number of other dimensions (see Cahill et al., 2012). Climate change effects on the phenology and interaction of some Cerrado's plants have already been suggested (Vilela, Claro, Torezan-Silingardi, & Del-Claro, 2017). The negative effect of climate change, evaluated via ENMs, has been also reported for several species of the Brazilian Cerrado realm, such as trees (Siqueira & Peterson, 2003), economical and edible plants (de Oliveira et al., 2015; Simon et al., 2013) and fauna (Aguiar, Bernard, Ribeiro, Machado, & Jones, 2016; Diniz-Filho et al., 2009). All these studies highlighted that the southern and south-western regions of the Brazilian Cerrado will be the areas where species will tend to move or will be the most climatically stable. Our results showed similar patterns; however, the central region of the Cerrado is also predicted as an area of species richness concentration. Probably, the differences between our results and the other studies can be caused by several factors such as the inclusion of soil data in our ENMs, our use of a greater species number than that of previous studies and the no dispersion scenario. Further methodological differences between our study and others, we emphasize that a large part of the regions that would potentially concentrate the greatest remnant richness also are those that will suffer an increase in the expansion and intensity of land use change.

Anthropogenically land uses such as plantation forest, cropland, pasture and urban areas significantly reduced species abundances and local species richness in comparison to primary vegetation (Newbold et al., 2015). We identified that the effects caused by land use change to the diversity of Cerrado plants will tend to increase, mainly due to the expansion of rangelands and croplands. South American rangelands are a key factor in the economy of many countries (such as Brazil) as they support grazing and livestock, and hence, it is expected that anthropic activities in these areas will intensify in future (Yahdjian & Sala, 2008). The increase in the effects of the agriculture expansion is in line with projections of future food demand, as this activity will need to produce almost 50% more human food, animal feed and biofuel to meet the demand in 2050 (FAO, 2017). In addition, the population growth rate and its tendency to concentrate in urban areas have led to a rapid change of food consumption pattern (FAO, 2017), followed by an increase of livestock products (Alexandratos & Bruinsma, 2012). In this sense, Brazil is considered one of the world's leading producers of agricultural commodities and, according to our forecasts, is the country (among the three here analysed) that will suffer the greatest impact of crop expansion on its plant diversity. Despite policies to halt deforestation in the Brazilian Cerrado, land use data shows that Cerrado continues to lose its natural cover. Forest areas and savanna lost 0.67 and 2.11 Mha, respectively, from 2010 to 2016, while farming expanded by 2.69 Mha (http://mapbiomas.org/stats). Bolivia and Paraguay are also among the countries that have suffered heavy losses of natural areas in South America, mainly as a result of farming and livestock activities, whose production is partially exported (Baumann et al., 2017; Fehlenberg et al., 2017; Redo et al., 2012). Therefore, they are also among the countries that supply global demands for agricultural goods, so the slowdown of their production would hardly occur. A strategic management of territories should simultaneously aim to expand PAs, since all three countries have ratified the Convention on Biological Diversity; and maintain or increase the production of agricultural commodities.

Our findings show the enormous potential distributional losses that could be caused by climate change alone within

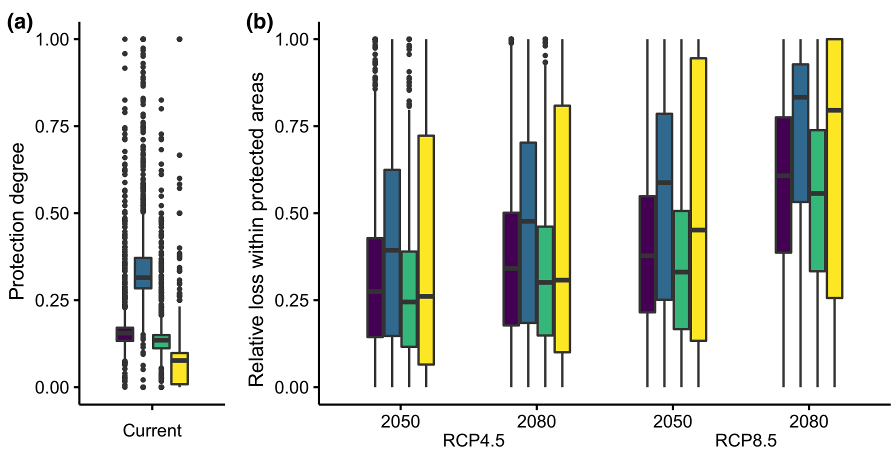


FIGURE 5 Boxplot of current protection degree (a) and future relative loss within PAs (b) of Cerrado's plant species for the whole study region (violet), Bolivia (blue), Brazil (green) and Paraguay (yellow). Future losses were forecasted for 2050 and 2080 under optimistic (RCP4.5) and pessimistic (RCP8.5) GHG emissions scenarios. The relative protection degree was calculated based on the ratio between the protected area of a species and its complete range. The relative loss in PAs was based on the ratio between the stable climatic area within PAs, that is, assuming no dispersal to new suitable environment condition, and the current distribution under protection. Protection and losses for each country were based on the ratio of the stable and lost species range within national PAs and the area occupied by the species within a nation

PAs. However, there are other threats related to the political, social and legislative spheres of a nation. For example, most of the conservation units in Paraguay do not have a management plan (DGPCB, 2016), the construction of a road through an important national park and indigenous area in Bolivia (Fernández-Llamazares et al., 2018), or the potential mining development within Brazilian PAs (Villén-Pérez, Mendes, Nóbrega, Córtes, & Marco, 2018), which would affect the conservation effectiveness in these countries.

At the national level and under current conditions, Bolivia showed the greatest protection degree of its national Cerrado flora. However, several of the species that occur there will be seriously affected by future climatic conditions, such effects are also observed in Paraguay (see Supporting Information Figures S6 and S7). This may be partly due to the fact that many of these species occur in these countries at the edges of their distributions, which may turn their populations susceptible in these regions (Thomas, 2010). Sometimes, these distributional edges can serve as a starting point towards new environmentally suitable regions (Channell & Lomolino, 2000). This latter effect could not be assessed here because we used a scenario in which species would not be able to disperse.

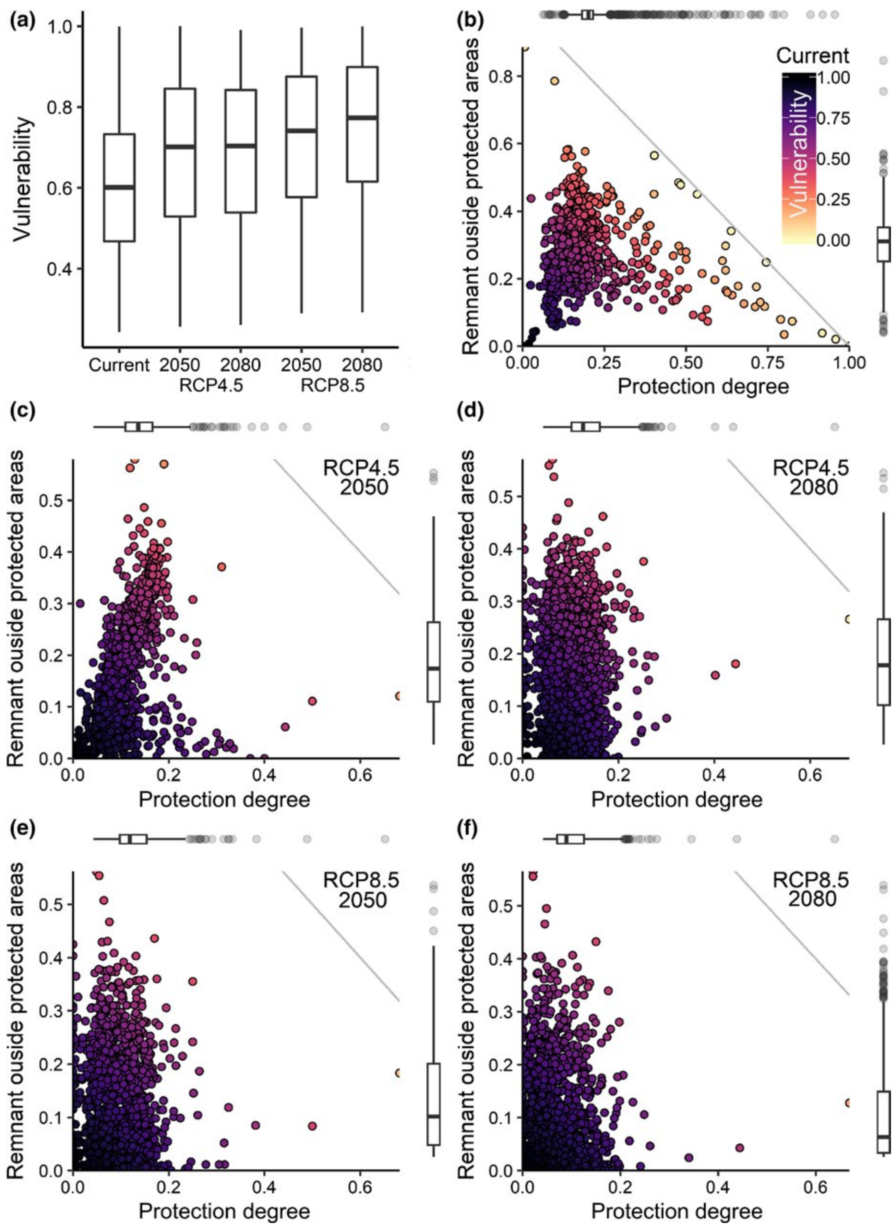


FIGURE 6 Boxplot of vulnerability values of 1,553 Cerrado's plant species for current condition and future land use and climate change under optimistic (RCP4.5) and pessimistic (RCP8.5) GHG emissions scenarios forecasted for 2050 and 2080 (a). Variability of species' vulnerability values (coloured points) within the relationships between the relative protection degree and the relative distribution remnant outside PAs for each GHG emissions scenario and time period (b–f). Each depicted point in the panels (b–f) represents a modelled species. Grey diagonal line represents the situation of no vulnerability

The expansion of PAs to reach Aichi Biodiversity Target 11 may be threatened by the expansion of land use (Pouzols et al., 2014). The relationship between land use and the distribution of the PA network highlights the necessity of proper management and monitoring of PAs, the creation of new ones in existing remaining areas and the recovery of disturbed lands. Actions recently proposed in the Brazilian Cerrado, such as expansion from croplands to pasturelands, productivity improvement, increase protections and land use planning among others (Strassburg et al., 2017), should be implemented in the neighbouring countries of Paraguay and Bolivia. It would be appropriate to face the loss of plant species in the Cerrado through global and regional actions. Actions covering the entire study area (Bolivia, Brazil and Paraguay) could improve conservation effectiveness. For instance, the allocation of PAs throughout the entire domain can be more effective than those implemented within each nation (Moilanen, Anderson, Arponen, Pouzols, & Thomas, 2013). Also, seeds collected from widely spaced populations can capture more genetic variability (Hoban & Schlarbaum, 2014). We showed that for most species with lower than 50% of their range within PAs, there are remnants of their distributions without protection, probably in private areas (Figure 6). This result suggests that for a general conservation plan to be successful, it must also consider the protection of species by creating private protected areas. However, such actions may not be sufficient or reachable under current conservation plans. For instance, in Brazil, there is a Forest Code to regulate deforestation on private lands, but it has been recently shown that the areas considered as legal for deforestation are much larger than those that would have to be restored to overcome such action (Vieira et al., 2018). The creation of private reserves may be considered an interesting way to maintain landscapes where species could persist. Nevertheless, actions within each nation would also be necessary in order to maintain its biological patrimony, this parochialism may also have positive points (Hunter & Hutchinson, 1994). New studies would be needed to assess what would be the priority areas needed for conserving biodiversity under the combined effect of climate and land use changes projections thorough entire territory.

5 | CONCLUSION

We demonstrated that climate and land use could cause great damage to the Cerrado flora by the years 2050 and 2080, even under the more optimistic scenarios of change. Unfortunately, the greatest intensity and extent of land use will be on the regions where the greatest species richness will be harboured. Conservation of Cerrado's plant species will also be seriously affected. The current PA network is not effective (and will not be) in safeguarding these species under current and future conditions, owing to the considerable loss of species distribution caused by climate change within the conservation units. The low protection degree coupled with the losses caused by climate change and land use will lead to most species being highly vulnerable to extinction. Given that the impacts of climate and land use are expected to be different for each country, conservation strategies for protecting the Cerrado's flora will have to be implemented at both transboundary/international and national levels.

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DATA ACCESSIBILITY

Occurrence records of plant species used to build ecological niche models are available under Dryad Accession https://doi.org/10.5061/dryad.8q3m5r0

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BIOSKETCH

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SUPPORTING INFORMATION

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

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